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INTEGRATED CIRCUIT PROJECTS Vol 1

INTEGRATED CIRCUIT PROJECTS

Volume 1

by

Forrest M. Mims, III

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PREFACE

If you've built a few transistor circuits and are anxious to try some more sophisticated projects, you're ready for integrated circuits (ICs). The IC will never replace the individual transistor, but ICs certainly simplify the assembly of circuits which might normally require up to dozens of transistors and other parts.

This book begins with an introductory chapter on project construction tips. Be sure to read this chapter, particularly if you're just getting involved in IC projects. The remainder of the book is completely devoted to construction projects. Each project has been built and tested to guarantee you a working circuit.

Each chapter includes a section on "Going Further" to provide you ideas about experimenting with or even modifying the basic project. Some of the projects are particularly well suited to modification. So if you like to experiment, get ready for some electronic tinkering.

The first set of projects use ICs in a digital mode. That's just a fancy way of saying the chief function of the ICs is to make logical "decisions" based upon the IC's internal circuitry. As you'll soon see, digital ICs can reverse (invert) the polarity of an electronic signal, count, store information, and decode complicated signals.

By connecting external components to some digital ICs, several kinds of interesting and useful oscillators and pulse generators can be constructed. Some digital ICs can even be used to amplify an incoming signal. Unusual applications for some of the digital ICs are described at the end of each chapter.

Finally, we conclude with projects using operational amplifier ICs—circuits designed to amplify instead of performing digital functions. The operational amplifier is a very flexible device; you'll see how to make it do much more than amplify.

I hope you find these projects as interesting to build as I did. With reasonable care, you will have no problems in getting each project to operate. Whether you build all the projects or just a few, your knowledge of semiconductor electronics will be significantly improved.

FORREST M. MIMS, III

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CHAPTER 1

PROJECT CONSTRUCTION TIPS

The recent availability of high-quality integrated circuits at very low cost represents a large development for experimenters. For the price of a transistor a few years ago, you can now buy a tiny ceramic, metal, or plastic package containing a chip with dozens of integral transistors, resistors, and diodes. This gives you the capability of putting together complex electronic circuits at far less cost and with fewer components than if you had to use individual transistors, diodes, and resistors.

This project book is an ideal way to help you get started in building your own integrated-circuit projects. Each of the chapters contains complete construction details for a project which uses at least one low-cost, readily available IC. To avoid the problem of finding hard-to-get parts, each project makes exclusive use of parts and supplies available from Radio Shack. Radio Shack has more than 2000 stores in all 50 states and Canada; so obtaining the parts should present no major problem. If, however, there is no Radio Shack store in your town, just write the company headquarters and request their latest catalog. The address is: Radio Shack, 2617 W. 7th Street, Fort Worth, Texas 76107. Each catalog contains a list of regional stores and their addresses; so you can send your order

directly to the store nearest you. If you prefer, you can send the order direct to Radio Shack headquarters in Fort Worth.

We'll get to the projects in a few pages, but first let's discuss some useful project construction tips. Whether you're a beginner or an experienced electronics hobbyist, you will find the following important information and helpful hints useful.

TOOLS AND TEST EQUIPMENT

A few low-cost tools will greatly simplify assembly of the IC construction projects in this book. Needle-nose pliers are ideal for preparing leads and connections for soldering. Diagonal wire cutters are necessary to trim wire leads. Insulation can be removed from wire leads with a pocketknife, but a wire stripper is faster and more convenient. A set of screwdrivers and a soldering iron will complete your basic tool kit.

All of these tools and several others (heat-sink clip for soldering, solder aid, and solder) are included in Radio Shack's Science Fair Electronic Tool Kit. Or, you can purchase the individual tools separately from the wide assortment available from Radio Shack.

All of the projects described in this book can be assembled and operated without the need for electronic test equipment. However, a low-cost volt-ohm meter (VOM) can come in very handy if it's necessary to troubleshoot any of the circuits. Also, a VOM is essential for checking power-supply voltages and the condition of batteries. A VOM can even be used to measure the current drain of a circuit. Also, VOMs are capable of measuring resistance, and they can be used to check the condition of a transistor (Chapter 4). VOMs are available from Radio Shack beginning at well under $10.

One of the most expensive, yet flexible, pieces of test equipment is the oscilloscope. This device displays a signal on a cathode-ray tube similar to the type found in a television set. It's not necessary to have a scope to build or use any of the projects described in this book, but, as we'll see later, a scope can come in very handy for certain applications. If you want to check out any of your projects with a scope, a polite call to a local television repair shop may result in an invitation to stop by for a quick test session. Scopes are also available in most high school and college electronics labs.

READING CIRCUIT DIAGRAMS

You're not going to need to understand electronic circuit diagrams to build any of the projects coming up, but a basic knowledge of schematic diagrams and symbols will contribute to your knowledge of the projects. Fortunately, reading circuit diagrams is no big problem, particularly since all the diagrams and symbols are easy to recognize and are very logical.

Integrated circuit symbols are particularly convenient, since they usually consist of a circle, square, triangle, or rectangle surrounded by numbered leads. Though each IC may contain dozens of individual components, it's not necessary to show them in the circuit symbol for the IC. Personally, I prefer to think of an IC as an electronic building block instead of a collection of individual parts.

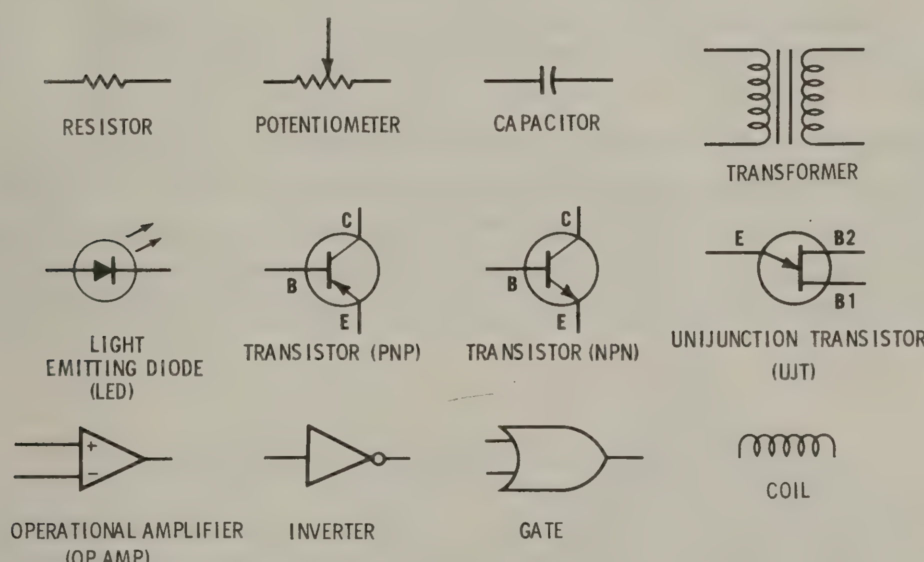


Figure 1-1. Common schematic symbols.

Most of the circuit diagram (schematic) symbols used in this book are shown in Figure 1-1. There are many others, and most are described in detail in the *Realistic Guide to Schematic Diagrams,* a Radio Shack publication.

CIRCUIT BOARD ASSEMBLY

Some transistor circuits are so simple that no mounting board is required. The various parts are just connected to-

gether and soldered in place. But most transistor and almost all IC projects require some kind of mounting board.

Nothing beats the perforated board for assembling experimenter projects. Building a circuit on a "perfboard" is called "breadboarding," and the resulting circuit can be quickly and conveniently modified by simply substituting parts for one another. A well-made breadboarded circuit will look neat and can even be used in a permanent application. Several kinds of pre-punched perforated boards are available from Radio Shack. The style used in most of the projects in this book is alternate grid with $\frac{1}{16}$-inch holes (catalog number 276-1392).

When a circuit has been designed, assembled, and checked out on a breadboard, you can permanently install it on a printed-circuit board if you want the utmost in permanence and neat appearance. Radio Shack markets a printed-circuit board kit which contains all the necessary chemicals, supplies, and instructions. A well-made printed-circuit project may not work any better than a perfboard project, but it will look better.

I prefer perfboards for most projects, since the option to modify the finished project is always available. But for projects that will probably never be altered or when extreme miniaturization is needed, I use printed circuitry. It takes more time, but the appearance and sturdiness of the finished project is always worth the extra effort.

MOUNTING INTEGRATED CIRCUITS

Integrated circuits come in three general configurations: flat pack, dual in-line, and circular can. Flat-pack ICs are difficult to work with because the leads are closely spaced; so all the projects in this book employ dual in-line or circular can types. Dual in-line ICs consist of a rectangular package about $\frac{3}{4}$ inch long and $\frac{1}{4}$ inch wide and made of ceramic or plastic. A notch at one end provides an indication of pin coding. A series of usually seven or eight connection pins run along each long side of the dual in-line integrated-circuit package (sometimes abbreviated DIP).

Circular can ICs resemble transistors, except they have more leads. Sometimes a small insulated post protrudes from the bottom of the can inside the circle formed by the leads. This

causes the IC to rest slightly above the circuit board for better cooling during soldering and operation.

Installing transistors on a perfboard is no problem, since they normally have only three leads, but typical ICs have 8, 14, or even 16 closely spaced leads or pins. Mounting ICs on a printed-circuit board is no problem, since you can draw or tape the lead or pin layout for a particular IC directly on the board. But once an IC is soldered to a printed-circuit board, it's very difficult to remove if it should be damaged or if you want to try another IC.

I prefer to build IC circuits on a perfboard with the help of sockets or adaptors for the ICs. When the circuit is working well, it can be transferred to a printed-circuit board or left on the perfboard. Sockets can be very convenient, particularly since they permit quick substitution of ICs. But since sockets have short pins at each contact point, you'll have to solder on extension leads or use a socket adaptor if you want to use a socket on a perfboard. A simple way to solder the extension leads is shown in Figure 1-2. Strip about $\frac{3}{16}$-inch insulation from one end of each lead and about $\frac{3}{8}$ inch from the opposite ends. Use needle-nose pliers to make a small bend in the short, exposed end; place the hook over a pin; solder the lead in place. An easy way to solder the leads is to hold the socket in place near the edge of your work table with a clothespin and suspend

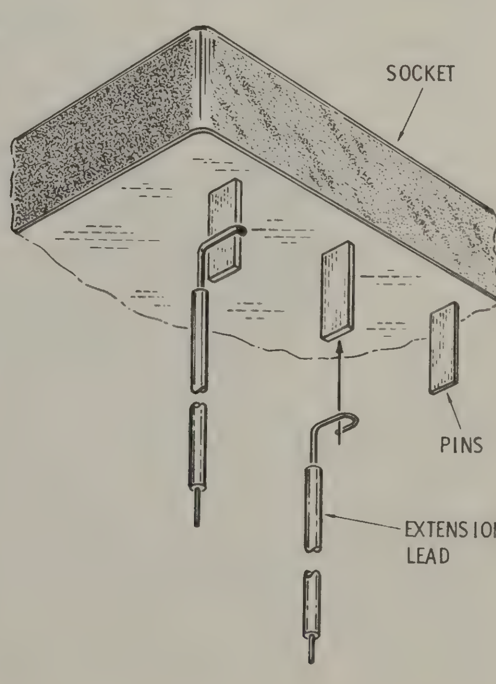


Figure 1-2. Soldering extension leads to an IC socket.

the wire leads from the socket pins. Then solder the leads one at a time, and the result will be a neat and convenient socket assembly. To mount the socket to a perfboard, simply thread the individual leads through two parallel rows of holes in the board.

Figure 1-3 shows a 14-pin IC socket (Radio Shack 276-027) with wire extension leads. Note that an IC has been inserted in the socket. Use care when installing and removing ICs from a socket. The pins of dual in-line types are easily bent and even broken by rough handling.

I always use the following procedure when installing a dual in-line IC:

1. Line up all pins on one side of the IC with the corresponding holes along one side of the socket.
2. Start each of the pins into its respective hole *without* pressing them into the socket.
3. Line up the remaining pins on the other side of the socket and start them into their holes. Sometimes it may be necessary to gently bend the pins toward the holes with a pencil.

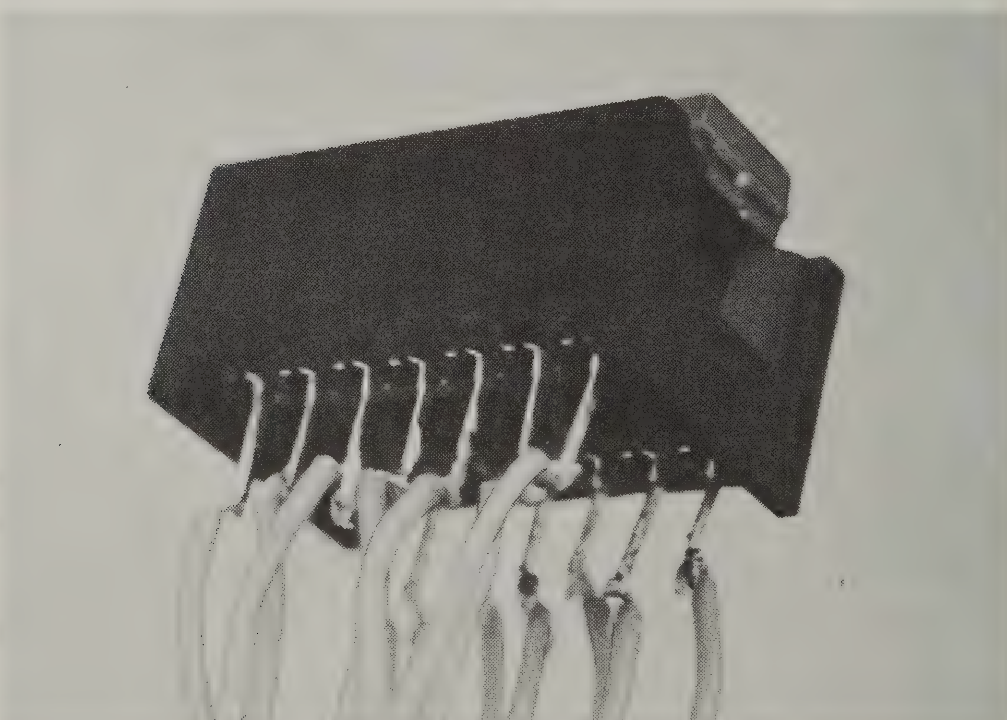


Figure 1-3. IC socket with extension leads.

4. Check all the pins to make sure each is started into its respective hole and use a rocking motion to press the IC firmly in place.

If you're unsure of this procedure, practice with a defective or inexpensive IC before trying a more costly unit. To remove the IC, simply insert a screwdriver under one end and gently lift upward. Switch to the other end and pry some more until it pops out of the socket.

Though sockets are very convenient and easy to use, I've found socket adaptors alone ideal for experimenter projects and have used them in most of the projects in this book. A socket adaptor is actually intended to be used with a socket. It consists of a small printed-circuit board containing a pin outline for either a circular or dual in-line IC. Copper conductors lead from each pin connection point to large solder pads around the edge of the board. The socket adaptor is assembled by inserting the pins from a socket into the holes on the bare (top) side of the board. Each of the pins is then soldered in place, and the socket-adaptor assembly is ready to receive an IC.

While the socket adaptor is intended for use with a socket, I've found them ideal for direct use with an IC. Instead of soldering a socket to the adaptor, I insert and solder an IC directly to the adaptor. The IC pin numbers can be conveniently marked next to each solder pad, and the IC number can be marked on the top surface of the adaptor.

It's easy to work with ICs on a perfboard once you have soldered either an IC or IC socket to the adaptor. Just solder lengths of hookup wire to each solder pad as shown in Figure 1-4. When the leads are all attached, install the adaptor on a perfboard by threading the wires through holes in the board as shown in Figure 1-5.

So far we've emphasized mounting dual in-line ICs, but the same mounting techniques can be applied to circular ICs, whether you use a socket, adaptor, or both. You might even want to try a handy mounting technique which works fine with circular ICs only. It's shown in Figure 1-6.

The idea is to force the IC into a rubber grommet and bend the leads over its sides. Remove the grommet, and you have a "spider" (a circular can IC supported by its leads) which can be easily inserted directly into a perfboard. The extra lead

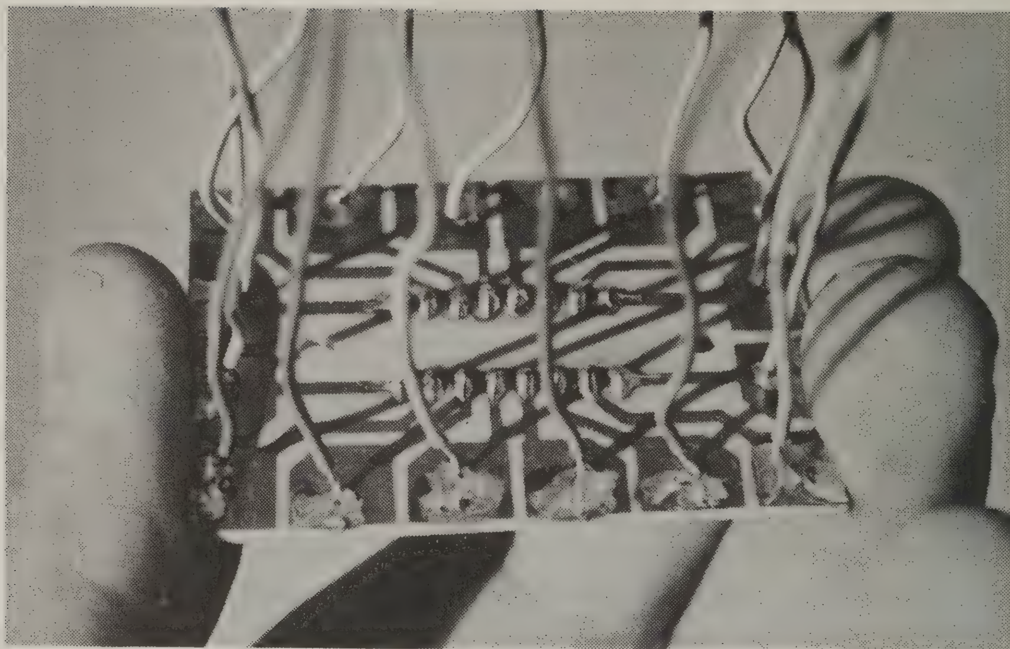


Figure 1-4. Wires soldered to the adaptor's solder pads.

length helps insure cooling when soldering to the leads, and you can easily remove the IC if it is damaged by just clipping each of the exposed leads.

No matter which IC installation technique you use, and you will probably want to try more than one, be sure to get the pin numbers right. Many an IC has died an untimely death due

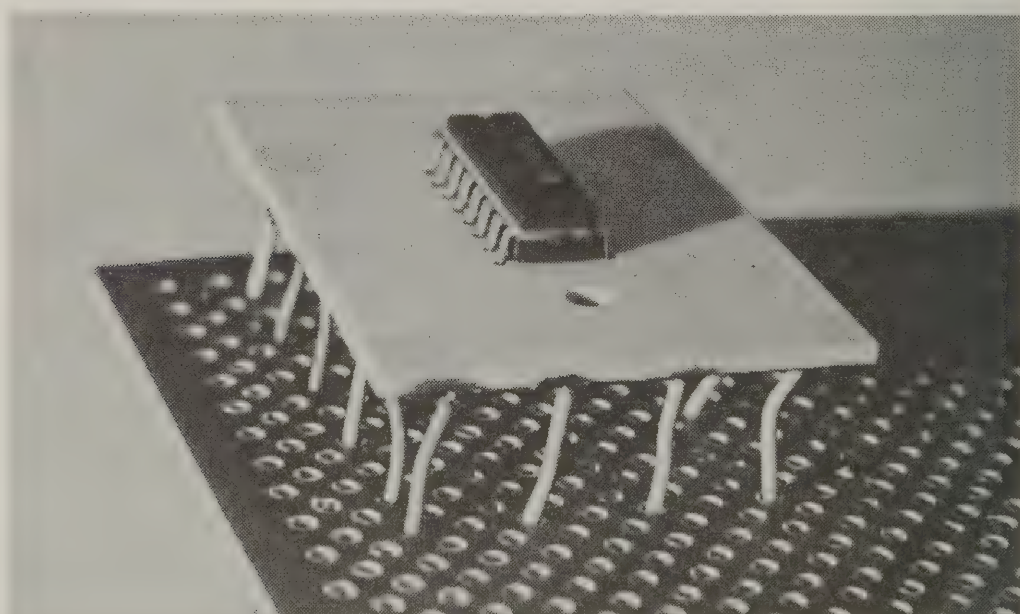


Figure 1-5. IC adaptor installed on a perfboard.

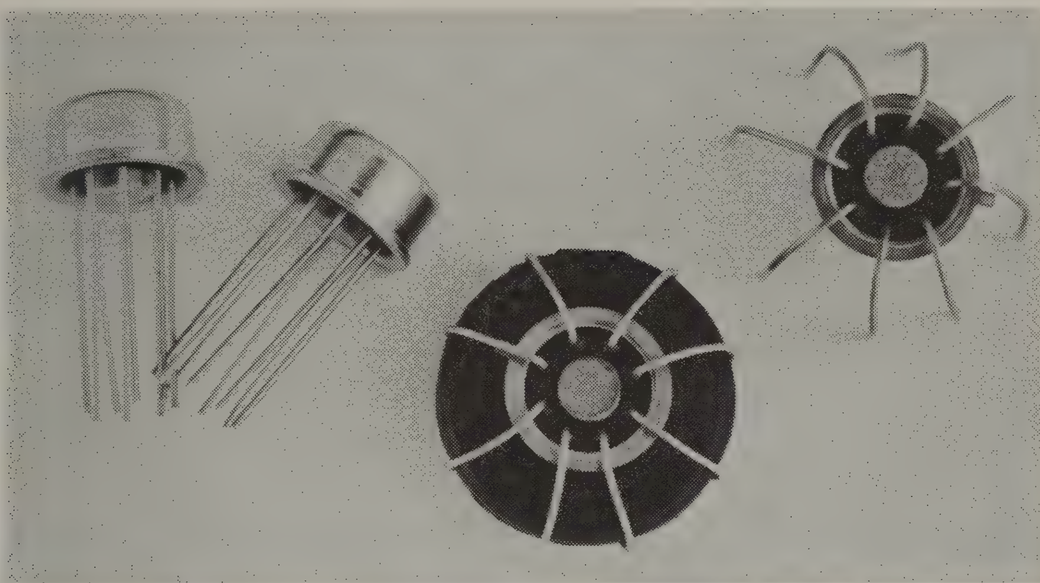


Figure 1-6. Lead preparation for upside down mounting.

to incorrect pin connections. Sometimes ICs can take incorrect connections without any harm, but don't count on it.

Correct pin diagrams for the ICs used in each of the projects in this book are provided in the circuit diagrams. However, it's easy to make a mistake and reverse the connections if you don't pay close attention to the outline. For example, all the pin diagrams in this book are shown with the IC viewed from the top. Since you have to turn the circular units over to see the leads, don't get confused and reverse the lead numbers.

By the way, if you're ever in doubt about pin connections, just check the manufacturer's data supplied with the IC. Radio Shack, for example, provides pin connections on either a small printed sheet or on the sales package itself.

SOLDERING

The most important part of assembling an electronic project is soldering the connections. It's mighty frustrating to track down a non-existent wiring error in a project when the problem was caused by a poor solder connection.

Even if you've had previous soldering experience, read over the following procedures for a review. If soldering is new to you, be sure to practice on some lengths of scrap wire before beginning work on one of the projects. Here are the steps to follow for a good solder connection:

1. Avoid using a soldering gun or high-power iron when assembling transistor circuits, since their heat may damage semiconductors and other components. Instead, obtain a soldering iron rated from 25 to 40 watts; tin the tip in accordance with the manufacturer's instructions.
2. Never use acid-core solder for soldering electronic components, since it is corrosive and may damage electronic parts. Always use rosin-core solder of the type sold by Radio Shack and other electronic stores.
3. To insure a low-resistance, permanent bond, always remove all grease, oil, paint, and other foreign matter covering parts to be soldered together. If necessary, use an abrasive such as sandpaper or a solvent.
4. Begin soldering a connection by first heating the joint where solder is to be applied. When the connection has been heated for a few seconds, leave the iron in place and apply solder to the connection (not the iron).
5. Allow the solder to flow throughout and around the connection for a second or so before removing the iron. Don't apply excessive solder or move the connection before it has cooled.
6. Keep the iron tip clean between soldering operations by wiping off accumulations of debris with a damp sponge or cloth.

If these six steps are followed, a good solder connection is easily made. A good connection will appear smooth and shiny, while a poor one will be dull.

The pin connections on IC sockets and socket adaptors are usually only about 1/8 inch or less apart and require care when soldering. With a little practice, though, you will be able to solder sockets and adaptors with ease. I always solder ICs or sockets to an adaptor by installing the component and inverting the board. A couple of clothespins clipped to the adaptor will keep it from sliding around the work bench. It's then a simple matter to touch the soldering iron tip to the junction of the copper on the board and the IC or socket pin. Let it heat for a few moments; then apply some small-diameter solder to the connection. Be sure the solder flows all around the pin. With a little practice, you will be able to solder the pins one after the other with just a few seconds per pin. The finished connections

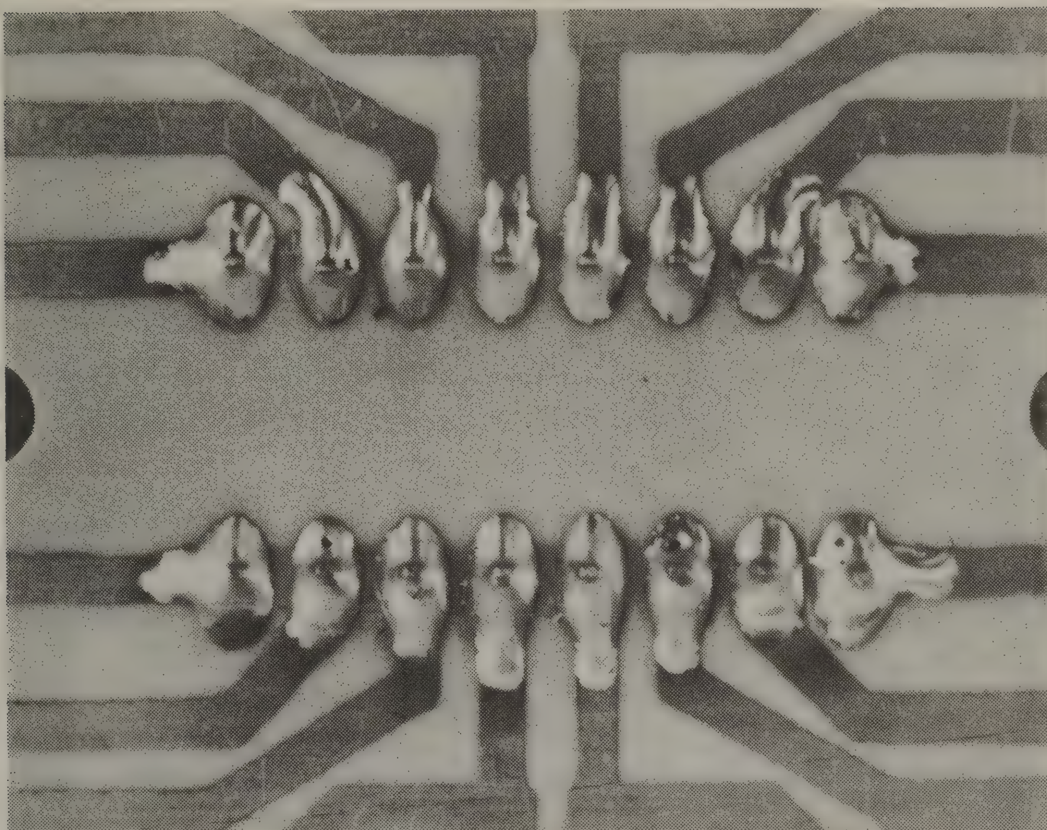


Figure 1-7. Finished connections.

should look like those shown in the dual in-line adaptor in Figure 1-7.

POWER-SUPPLY SELECTION

Thanks to a wide range of commercial power supplies and low-cost batteries, powering the projects in this book will present no problem. Two of the projects have a built-in supply which converts the 120-volt household alternating current into the low-voltage DC required by the IC. The others can be operated by any of several batteries or commercial power supplies.

For portability and convenience, you can choose from a wide variety of commercial cells (batteries). (Technically, a battery is composed of two or more cells. However, for ease of discussion, we will use the terms interchangeably.) In addition to conventional zinc-carbon dry cells, there are mercury, alkaline, and nickel-cadmium cells. The latter cells can be recharged up to 500 times, so their initial high cost is well worth the investment. Alkaline cells last up to ten times longer than standard

zinc-carbon units, so even at a high price they are still a good buy.

The projects described in this book require from 4½ to 9 volts for proper operation; so you will need several individual 1½-volt cells or higher voltage batteries to get the correct voltage. If you use several 1½-volt cells, battery holders are far more convenient than soldering the cells together. If you do solder to a battery, make sure it's a conventional zinc-carbon unit and not one of the mercury, alkaline, or nickel-cadmium types. The latter cells may explode if sufficient heat is permitted to build up inside them—*never* solder to them.

While batteries are great for portability and convenience, line-operated power supplies are far more flexible and efficient in the long run. Watt for watt, practically no source of power is as expensive as battery power. Radio Shack offers several low-cost power supplies beginning at well under $10. The most economical unit is a kit (catalog number 28-104) that will operate any project requiring from 6 to 9 volts. For a bigger investment, you can get a solid-state variable DC power supply. Radio Shack's 22-126 is continuously variable from 0–24 volts at up to 1 amp and is ideal for transistor and IC projects and experiments.

While line-operated supplies cost more than batteries initially, they should last indefinitely and in the long run are considerably more economical than repeated battery replacement. Personally, I prefer batteries for all portable equipment, but I always use a line-operated power supply for experimental circuits.

CHAPTER 2

FLIP-FLOP DEMONSTRATOR

The flip-flop is an electronic logic circuit which is always in one of two stable states. The only way to change the state of the flip-flop is to jolt it with a brief voltage pulse. You can think of a flip-flop as being the electronic counterpart of a mechanical switch.

The very simple action of a flip-flop may not sound useful or important, but flip-flops are used in all sorts of computer operations. By connecting flip-flops to one another, it's possible to count an incoming train of pulses. In other words, you can use flip-flops to add. And, since multiplication is just repeated addition, you can also use flip-flops to multiply. Furthermore, flip-flops always remain in either of two stable states. Even after a very brief trigger pulse, they can be used as memory elements. A series of flip-flops used to temporarily hold data in an electronic calculator or computer is often called a *storage register.*

The simple circuit described here will give you an excellent idea of just how a flip-flop operates. Several years ago you would have had to invest a few dollars to obtain an integrated circuit flip-flop, or go to the trouble of putting together a dozen or more parts to make up one on your own. Thanks to the large scale use of flip-flops by industry, you can now buy individual units from Radio Shack and other electronics distributors for

well under a dollar each. For a little over a dollar, you can get a four-bit latch, an IC containing four interconnected flip-flops and used to store data.

HOW IT WORKS

In Chapter 1, I said it's convenient to think of an integrated circuit as an electronic building block instead of a collection of individual components. Nevertheless, it's still helpful to have some knowledge of what happens inside that "building block," so let's look inside a simple flip-flop.

The simplest flip-flop consists of two transistors, several resistors, and maybe a few capacitors. When the circuit is connected to a source of current, one of the transistors turns on, and the resulting current flow keeps the other transistor off. However, a brief pulse applied to the circuit turns off the first transistor and permits the second one to turn on. The second transistor's current flow keeps the first transistor off, until another pulse is applied and the first transistor is again turned on. The process continues each time a pulse is applied.

Integrated circuitry permits dozens of components to be formed on a tiny silicon chip, so an IC flip-flop can have far more parts than the simple circuit we've just considered. For example, the 923 flip-flop we're using in this project has 15 transistors and 17 resistors. The extra components give the flip-flop operating stability and provide several operating features not found in simpler versions.

The demonstrator flip-flop described here incorporates a light-emitting diode (LED) to indicate the device's output state. Referring to the circuit diagram in Figure 2-1, note how the Count switch activates the flip-flop by feeding a positive potential to the input, pin 2. The LED should light every other time the Count switch is pressed.

Transistor Q1 serves as a lamp driver by permitting a higher current flow through the LED than if the IC alone were used. Since the LED requires relatively little current, the IC will drive it directly, but using Q1 in the demonstrator is important since it teaches the operation of a lamp driver. In operation, the IC turns Q1 on and permits current to flow through the LED every other time the Count switch is pressed. In this way the transistor, not the IC, acts as a switch for the LED.

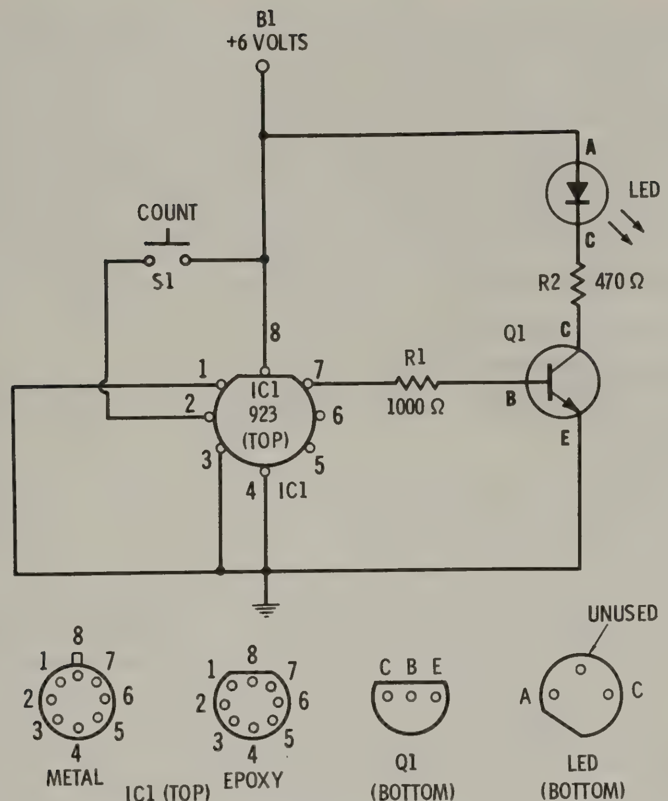


Figure 2-1. Flip-flop demonstrator circuit.

We'll discuss how to connect flip-flops together to perform more complicated operations in the section on "Going Further." But first, let's actually hook up a flip-flop and see if it works as advertised.

CIRCUIT ASSEMBLY

The IC socket adaptors we discussed in Chapter 1 can prove very useful in IC circuits which require only a few additional components. While all the remaining projects in this book are assembled on perforated boards, I've built this one directly onto a socket adaptor. You'll find that some of the following projects can also be built using this technique.

Begin assembly by drilling a ¼-inch hole in a corner of the socket adoptor. This will be used for S1, as shown in the pictorial in Figure 2-2. Drill the hole in the copper strip leading from the square copper solder pad on the upper right corner of the back side of the board. Be very careful when you are drilling. Do not drill into the copper conductors on either side of the copper strip.

Next, install the IC by spreading its leads slightly and placing them in the circular array of holes from the top (bare) side of the adaptor board. If you prefer, you can bend the leads around a rubber grommet to make a "spider," as shown in Figure 1-6 in the preceding chapter. If you do, be sure to reverse the connections to the IC from those shown in the pictorial, since the IC will be upside down.

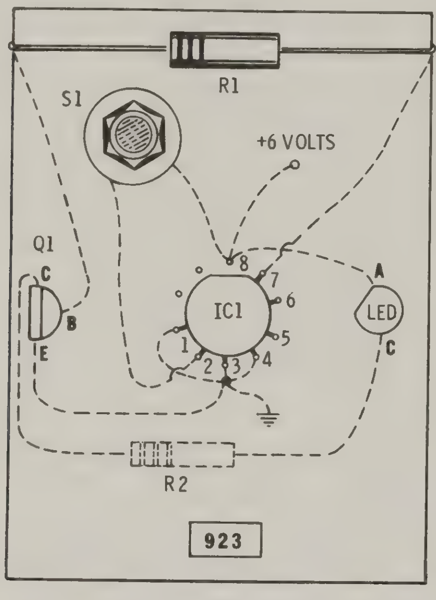


Figure 2-2. Flip-flop demonstrator pictorial.

The IC is made of very hard plastic. It has a flat area on one side which denotes pin 8. Place pin 8 in the hole nearest the top of the adaptor board, as shown in Figure 2-2, and leave two empty holes between pin 8 and pin 1. This will prevent a possible short circuit if the switch happens to touch both these holes when it is installed.

When the IC is in place, carefully solder each lead to the copper foil on the back side of the board. Use care to avoid bridging excess solder across adjacent connections. If you are a novice at soldering, be sure to review the soldering procedures outlined in Chapter 1 before attempting to solder the IC to the adaptor board.

After the IC is in place, solder a wire lead across the copper solder pads connected to the ICs pins 3 and 4 and from there to pin 1's pad. Be sure the wire is insulated where it crosses the pad connected to pin 2. I find it helpful to mark the respective pin numbers on each solder pad with a permanent marking pin. This prevents wiring errors. Make sure you mark

the numbers based on a *top* view of the IC, or you will reverse them.

Next, install the switch from the back (copper side) of the adaptor and secure it in place with its retainer nut. Install R1 across the top of the board by bending its leads and soldering one of them to the solder pad connected to the IC's pin 7.

When R1 is in place, insert transistor Q1's leads through the hole on the left side of the board. You can then solder Q1's base to the remaining lead of R1. Be sure to refer to the pin diagram for Q1 in Figure 2-1 to make sure you don't mix up the lead connections.

Next, solder Q1's emitter lead to the solder pad connected to pin 1 of the IC. If you installed the IC as shown in Figure 2-2, pin 1 will be connected to the solder pad directly below and adjacent to the hole in which you installed Q1.

Continue assembly by installing the light-emitting diode (LED) in the hole in the adaptor board opposite the transistor and IC. Be sure to connect the leads correctly. The LED is a diode, and unlike conventional lamps, it will only work when connected in the proper direction. The LED has a flat area on its side, and the lead closest to this key, the anode, is soldered to the solder pad connected to the IC's pin 8. You will need a 1-inch length of insulated hookup wire to reach the pad.

If there is a middle lead on the LED, cut it off. Then solder the remaining lead to R2. R2's remaining lead is soldered to Q1's remaining lead, the collector. Note that R2 is mounted to the back of the board. It will stay in place without shorting its leads to other components if you solder the LED and Q1 leads reasonably close to R1 and clip off the excess lead lengths.

Complete construction of the circuit by soldering short lengths of hookup wire to each terminal of the switch. Use a 1-inch length to reach pad 8 and a 1¾-inch length to reach pad 2. When these leads are soldered to the pads, assembly of the circuit is complete and your demonstrator flip-flop will look something like the one shown in Figure 2-3.

TESTING AND OPERATION

Inspect all the solder connections and make sure all the semiconductors (the IC, LED, and Q1) are properly connected. Pay particular attention to the pin numbers of the IC.

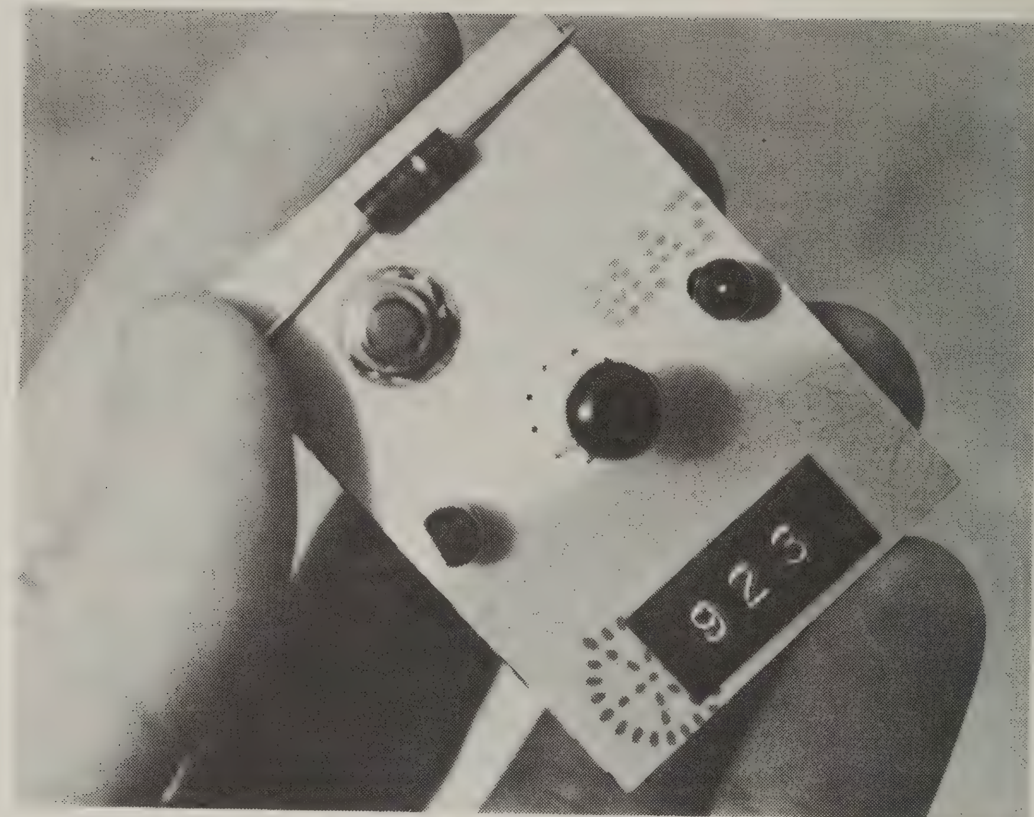


Figure 2-3. Assembled flip-flop.

When the circuit has been inspected, connect clip leads from a 6-volt power supply to the appropriate solder pads. (Pin 8 should be positive and pins 1, 3, and 4, which are all soldered together, negative.) I used a line-operated power supply to get the 6 volts, but you can use a 6-volt lantern battery or three or four $1\frac{1}{2}$-volt dry cells installed in a battery holder to give the required 6 volts.

The LED should turn on when the battery or power supply is connected. Press the Count switch and the LED will be extinguished. But press the switch again, and the LED will again turn on. Every other time you press the switch the LED should turn on.

Don't worry if the circuit seemingly fails to flip each time the switch is pressed. Mechanical switches rarely make firm contact the first few milliseconds they are pressed, and the result may be several very fast on-off pulses. This is called switch "bounce." The flip-flop responds to even very fast pulses; so it may appear to have stayed in one state when the switch was pressed, when it may actually have changed states twice or

even more. This usually happens so fast you cannot see the LED briefly flash on or off.

If the circuit doesn't flip in response to the input pulses from the switch, check the wiring and IC pin connections for possible errors and make sure the circuit is receiving power. Too little voltage will keep the circuit from operating at all, while too much voltage will heat up and possibly destroy the IC.

GOING FURTHER

Since we are only looking at one side of the flip-flop, the LED is on only during alternate cycles of the Count switch. By using two LEDs (the second connected to the flip-flop's other output point), one LED will be on each time the switch is pressed, but both will never be on at the same time. This arrangement will make it much easier for you to visualize the flip-flop action of the IC.

To modify the demonstrator for two LEDs, refer to Figure 2-4. This circuit is identical to the original one in Figure 2-1, but a second lamp driver circuit consisting of Q2, R3, R4, and LED 2 has been added. The emitters of both LEDs go to the positive power-supply connection (IC pin 8). The only differ-

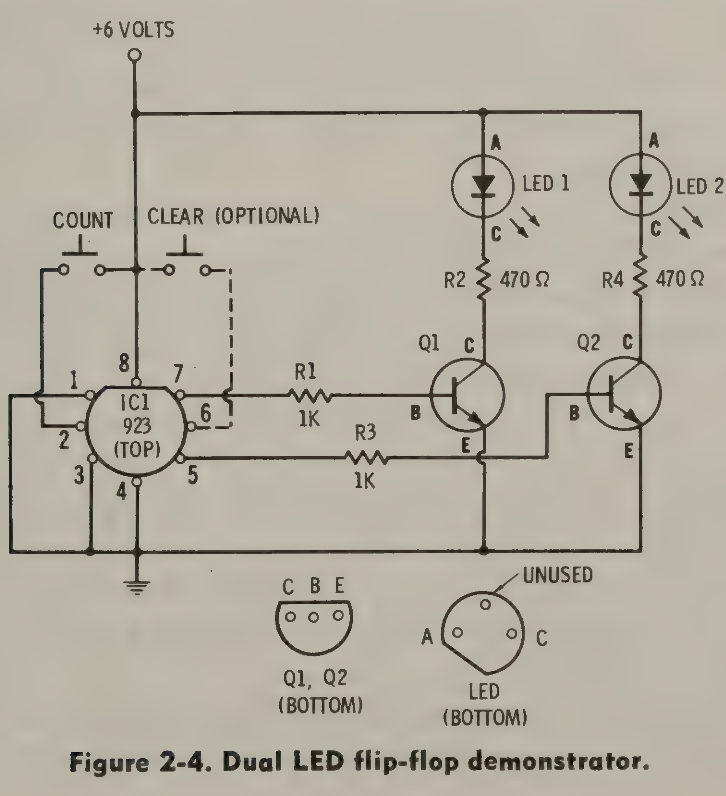


Figure 2-4. Dual LED flip-flop demonstrator.

ence is that the base of Q2 in the second lamp driver circuit goes to pin 5 through resistor R3.

Since pins 5 and 7 are the two output connections for the 923 flip-flop, one of the two will always indicate an output voltage, while the other will always indicate no output. By pressing the Count switch, the state of the output voltages will reverse and hold the new state until the flip-flop is once again triggered by pressing the Count switch. The result is that one LED will always be on and the other off until the Count switch is pressed. The LEDs will then "flip-flop" as they exchange conditions and wait for the next count signal.

Another useful modification to the basic demonstrator is adding a *Clear* switch (another switch like S1) between pins 6 and 8. Pressing this switch will always return the flip-flop to its initial state, no matter how often the Count switch has been pressed. If you've operated an electronic calculator, you have no doubt seen a Clear key. This key performs exactly the same function as the Clear switch in this simple demonstrator circuit.

This very basic demonstrator shows how a low-cost, yet complete, digital IC can be used to both count and store an incoming signal. Of course the circuit isn't practical as is, but if you were to connect the output of this flip-flop to another and its output to still another and so forth, you would have a counter (adder) capable of receiving a series of incoming pulses. It would also display the total number of pulses received on a bank of LEDs.

The count would at first seem meaningless, since the actual number would be encoded by a series of on and off LEDs. Actually, the code is a two-digit number system quite different from our ten-digit or decimal system. The two-digit system is called the binary system and is very handy to use with electronic counting circuits like flip-flops.

While binary numbers are handy for electronic circuits, they are clumsy for you and me to use. That's because the binary system has only two digits, 0 and 1, and a single-digit decimal number may be the equivalent of up to four binary digits. For example, the decimal number 9 is expressed in binary form as 1001.

Fortunately, there are electronic decoding circuits built into some ICs which can automatically convert binary numbers

into decimal signals, which can be displayed on a readout tube. We'll actually build a binary to decimal readout unit in Chapter 4, but first let's look at another very useful integrated circuit, the inverter.

Table 2-1. Flip-Flop Demonstrator Parts List

Item	Description
B1	Battery, 6 volt (see text)
IC1	RTL JK 923 Flip-Flop (276-023)
LED	Light-emitting diode (276-026)
Q1	Transistor, NPN (276-2016)
R1	Resistor, 1000 ohm
R2	Resistor, 470 ohm
SW1	SPST push-button switch (275-1547)
Misc	IC socket adaptor (276-028), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

CHAPTER 3

INTEGRATED-CIRCUIT LAMP DRIVER

In the last chapter, I showed you how to use a single transistor as a lamp driver. What we essentially did was let the transistor conduct the current required to operate a light-emitting diode (LED) by turning on the transistor (thus the LED) with a signal from the IC.

In this chapter I'm going to show you how to use an integrated logic circuit, the inverter, to drive an LED. Since the IC we'll be using has six separate inverters, you'll be able to experiment with a variety of modifications and connections to learn more about both lamp drivers and digital logic.

HOW IT WORKS

An inverter is a simple transistor circuit which accepts an input signal of one polarity and changes it to the opposite polarity. For example, a series of positive pulses entering an inverter will emerge as a series of negative pulses.

To see how this happens, refer to Figure 3-1. This illustrates a very basic transistor circuit called the common-emitter amplifier. Why common-emitter? Because the transistor's emitter is common to both the input and output of the circuit.

In operation, a positive signal at the input causes Q1 to turn on and conduct. This causes a current flow through the resistor,

and the result is a negative output signal at the collector of the transistor. Reverse the polarity of the input signal, and the output signal will be positive.

Since this inverter is simply a single transistor amplifier, it's easy to use it as a lamp driver. All that's necessary is to insert an LED between the resistor and the positive battery terminal. If the anode of the LED is connected to the positive terminal of the battery, a positive state at the input of the circuit will turn the LED on. Otherwise, the LED will be off.

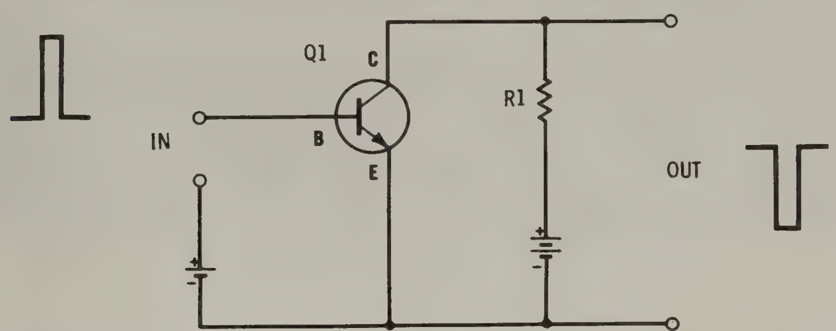


Figure 3-1. Basic common-emitter circuit.

This operation is reversed if the LED is connected across the collector-emitter terminals of the transistor. Now the LED will normally be on, but a positive state at the input will turn it off. For this variation to work properly, the anode of the LED must be connected to the transistor's collector.

You can obtain ICs which contain a single inverter, but your best buy is the hex inverter. Hex comes from a Greek word meaning six; so a hex inverter is a single IC containing six individual inverters. These inverters are more sophisticated than our little demonstration model in Figure 3-1, and each contains 4 transistors, 4 resistors, and 2 diodes.

Figure 3-2 shows how to connect one of the six inverters in a hex inverter (Radio Shack 276-1802) as an LED driver. Since there is normally no input signal on the inverter, the LED is normally on. In binary terminology, a "0" signal on the input gives a "1" on the output. If a signal is placed on the input, the LED will turn off. Again, in binary a "1" on the input gives a "0" on the output.

Let's put the circuit together. It's the simplest project in this book, and total assembly time should only be a few minutes, once the IC is soldered to an adaptor board or a socket is given connector leads.

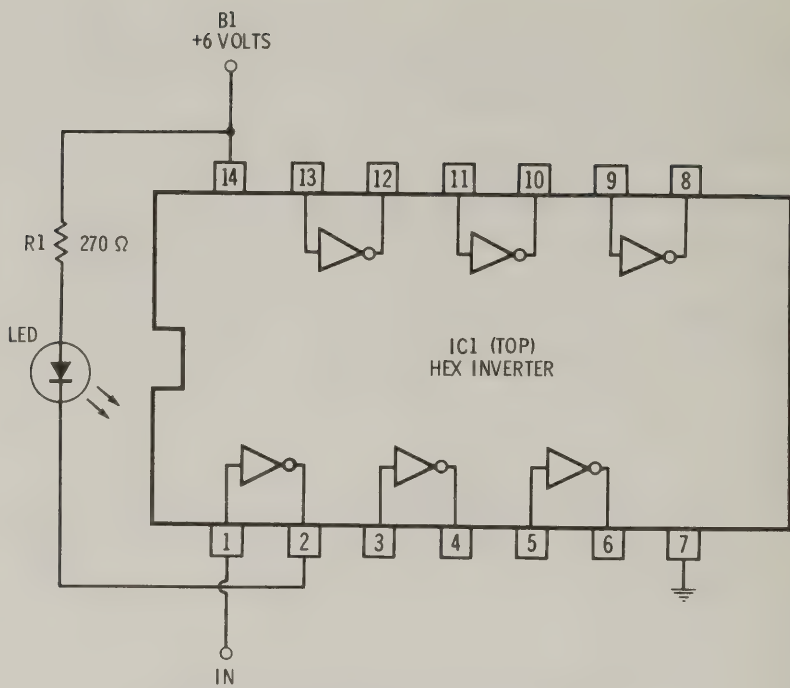


Figure 3-2. Hex inverter lamp driver.

CIRCUIT ASSEMBLY

A pictorial view of the completed IC inverter lamp driver is shown in Figure 3-3. I used an IC socket (extension leads soldered to each pin), but you can solder the IC or the socket to a

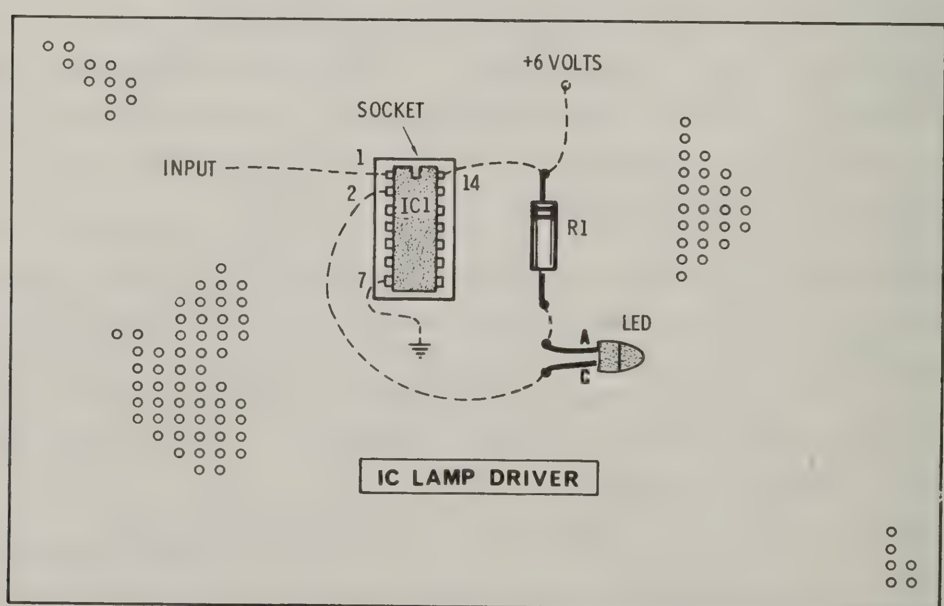


Figure 3-3. Hex inverter LED driver pictorial.

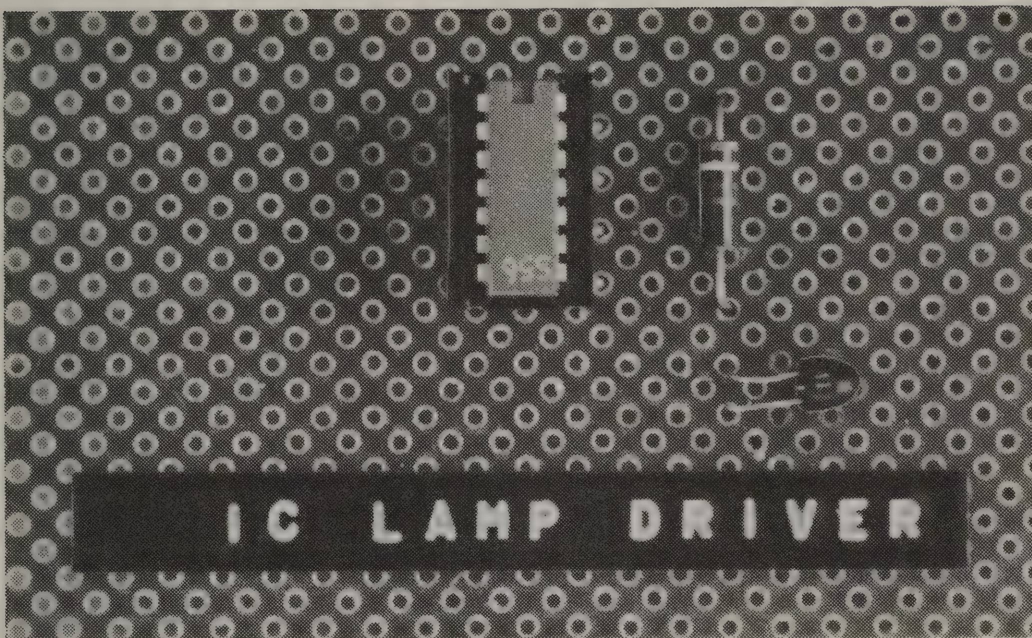


Figure 3-4. Assembled lamp driver.

socket adaptor board if you prefer. Since only one of the inverters in the IC is used, you only have to solder connection leads to the socket pins or adaptor board solder pads—which connect to pins 1, 2, 7, and 14 on the IC. The pin diagram for the IC is shown in Figure 3-2. Note that one end of the IC, a dual in-line unit, has a notch formed into it. Looking at the IC from the top and with the notch to your left, pin 1 is the pin below the notch and 14 the one above the notch. Mount the IC socket or adaptor to the perforated board by threading the connection leads through holes in the board. Bend the leads on the resistor, insert them through the perfboard, and solder one lead to the IC's pin 14 connection lead. Solder the remaining resistor lead to the anode lead of the LED. If you use a Radio Shack 276-026 LED, the anode is the lead nearest the flat area on the side of the epoxy package. Complete assembly by soldering the LEDs cathode lead to the IC's pin 2 connection lead. If there is a middle lead between the anode and cathode leads, clip it off and discard it. The completed circuit should resemble the one shown in Figure 3-4.

GOING FURTHER

If you want to make the inverter lamp driver into a permanent demonstrator circuit, connect a push-button switch be-

tween pins 1 and 7. In this way you can demonstrate both operation of a lamp driver and the principle of polarity inversion by simply pressing the switch.

There are several other things you can do with the basic circuit, and I suggest you try some of them. The first is to simply disconnect the inverter connected to pins 1 and 2 and try any of the other inverters in the IC. The pin numbers are all shown in Figure 3-2. You will find that each individual inverter operates identically to the others, in that signal inversion always occurs.

Next, try a trick sometimes used by circuit designers faced with the problem of driving a relatively high current lamp. Connect all the inverters in parallel by connecting pins 1, 3, 5, 9, 11, and 13 together and doing the same with pins 2, 4, 6, 8, 10, and 12. Now you have six times the current capability of a single inverter, and the resulting circuit operates as a standard inverter, even though it employs 24 transistors, 24 resistors, and 12 diodes.

TESTING AND OPERATION

Check the completed circuit to make sure there are no wiring errors. The circuit will not operate if the IC is connected incorrectly or the LED leads reversed. Next, connect 6 volts to the circuit with a line-operated power supply or batteries. I used a power supply, but you can use a 6-volt lantern battery or three or four 1½-volt dry cells connected in series to give 4½ to 6 volts.

When the power is applied, the LED should turn on and glow bright red, showing that the inverter is responding to a "0" input state with a "1" output state. But when you apply a "1" input signal by touching the input lead of the inverter (in this case pin 1 of the IC) to ground (pin 7), the LED will turn off and indicate a "0" output state. In a practical circuit, the input signal would probably be provided by an IC or transistor.

If the circuit fails to operate, recheck all the wiring. Also, make sure you're touching the input lead (pin 1) to pin 7.

So far we've emphasized the inverter as a lamp or LED driver, but it's more interesting to explore its logic capability. You've already seen how an inverter changes a signal from binary "0" to "1" or the reverse. To see how a signal can be

sent through an inverter circuit *without* this change of state, disconnect the LED from the IC's pin 2 connection lead in the original circuit and connect pin 2 directly to pin 3. Reconnect the LED into the circuit at pin 4. Now you have two inverters in series, and even with the battery connected, the LED will be off. Touching the IC's pin 1 connection lead to pin 7, however, will turn the LED on. In binary notation, when there is no input, a "0" is inverted to give a "1" which is inverted to give a "0." Providing an input signal by touching pin 1 to pin 14 provides the opposite binary sequence.

If you want to, you can carry this procedure for all of the individual inverters in the IC. Even numbered arrangements will produce no inversion, while odd numbers of inverters will always give an inverted output. With appropriate electronic test equipment, such as an oscilloscope, you would see a slight delay between the application of an input voltage and the reaction of the lamp. This is called *propagation delay* and occurs because electrons require a finite time to activate any electronic circuit. The propagation delay increases as more inverters are connected in series, but is not increased by connecting them in parallel.

For more on inverters as logic circuits, consult any good reference on electronic logic. You will find that numerous logic circuits employ self-contained inverters in order to satisfy internal requirements. For example, *gates* are logic circuits which transmit an incoming signal or state only when certain input conditions are satisfied. An AND gate has two or more inputs. When there is a signal (binary "1") at only one of the two inputs, there is no output signal. But when there is a signal at both inputs, the gate issues an output signal (binary "1").

Table 3-1. IC Lamp Driver Parts List

Item	Description
B1	Battery, 6 volt (see text)
IC1	7404 hex inverter (276-1802)
LED	Light-emitting diode (276-026)
R1	Resistor, 270 ohm
Misc	Perforated board (276-1392), 14-pin socket (276-027), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

The basic AND gate and other logic circuits can be made to perform various other operations by adding an inverter to the output. In the case of the AND gate, adding an inverter produces a NAND gate with operating characteristics opposite those of the AND gate. In binary terms, a "1" on either input gives a "1" on the output; a "1" at both inputs gives a "0" on the output.

CHAPTER 4

BINARY TO DECIMAL DECODER

In Chapter 2, we saw how an important digital logic circuit, the flip-flop, uses a two-digit ("0" and "1") number system to count and add. While the binary number system is ideal for electronic circuits, it's very impractical for you and me. Not only are we used to the ten-digit decimal system, but the binary system is inherently clumsy since it has only two digits. For this reason, larger binary numbers will have far more digits than their decimal counterparts.

Fortunately for anyone who works with digital electronic equipment, and that includes you, there is a very complex integrated circuit called a BCD to 7-segment decoder/driver. It makes possible the conversion of a binary number into a series of electrical signals which activate the appropriate segments of a visual readout device. The decimal equivalent of the binary input to the decoder can then be read directly from the readout.

BCD means *Binary Coded Decimal,* and by building this project you will learn quite a lot about both BCD and digital logic. Since the circuit incorporates a line-operated power supply, you will also learn some power-supply basics. Finally, since the output of the BCD to 7-segment decoder/driver is fed into a 7-segment fluorescent display tube, you will also learn about one of the most popular visual readout devices in present use.

HOW IT WORKS

This project consists of four basic subsystems: power supply, BCD to 7-segment decoder/driver IC, display tube drive circuitry, and the display tube itself. To simplify the description of how the entire system operates, I'm going to describe each of the subsystems one at a time.

Power Supply

To see how the power supply works, see the circuit diagram for the entire decoder circuit in Figure 4-1. The power supply consists of transformer T1, rectifier bridge B1, filter capacitor C1, and resistors R1–R4.

In operation, 120 volts of alternating current flowing in the primary coil of transformer T1 induces an alternating current in the secondary coil. Since the secondary has fewer turns than the primary, its output voltage is only about 30 volts. The decoder circuit requires direct current for proper operation; so the 30 volts is converted to DC by the rectifier bridge (B1). Four individual diodes can be used to rectify an alternating current, but the module used here is far more convenient. After rectification into dc, the pulsating current is smoothed by filter capacitor C1. The display tube only requires about 25 volts for proper operation, and this is obtained with dropping resistor R1. Dropping resistor R2 supplies the approximate 5 volts required by the decoder IC, and R3 and R4 supply the approximate 1½ volts required by the display tube's filament. Actually, only one resistor is needed for R3 and R4, but the addition of resistor R3 permits the tube's brightness to be adjusted.

BCD to 7-Segment Decoder IC

The BCD to 7-segment decoder/driver IC used in this project is a 7447 (Radio Shack 276-1805), a 16-pin dual in-line unit. Not long ago this IC was prohibitively expensive for most experiments, but now you can purchase it for a little over $2.00.

Internally, the 7447 is a maze of gates and inverters. A look at the logic diagram on the 7447 specification sheets reveals some 32 gates and 12 inverters. If each gate and inverter contains an average of 4 transistors, that's a total of approximately 176 transistors.

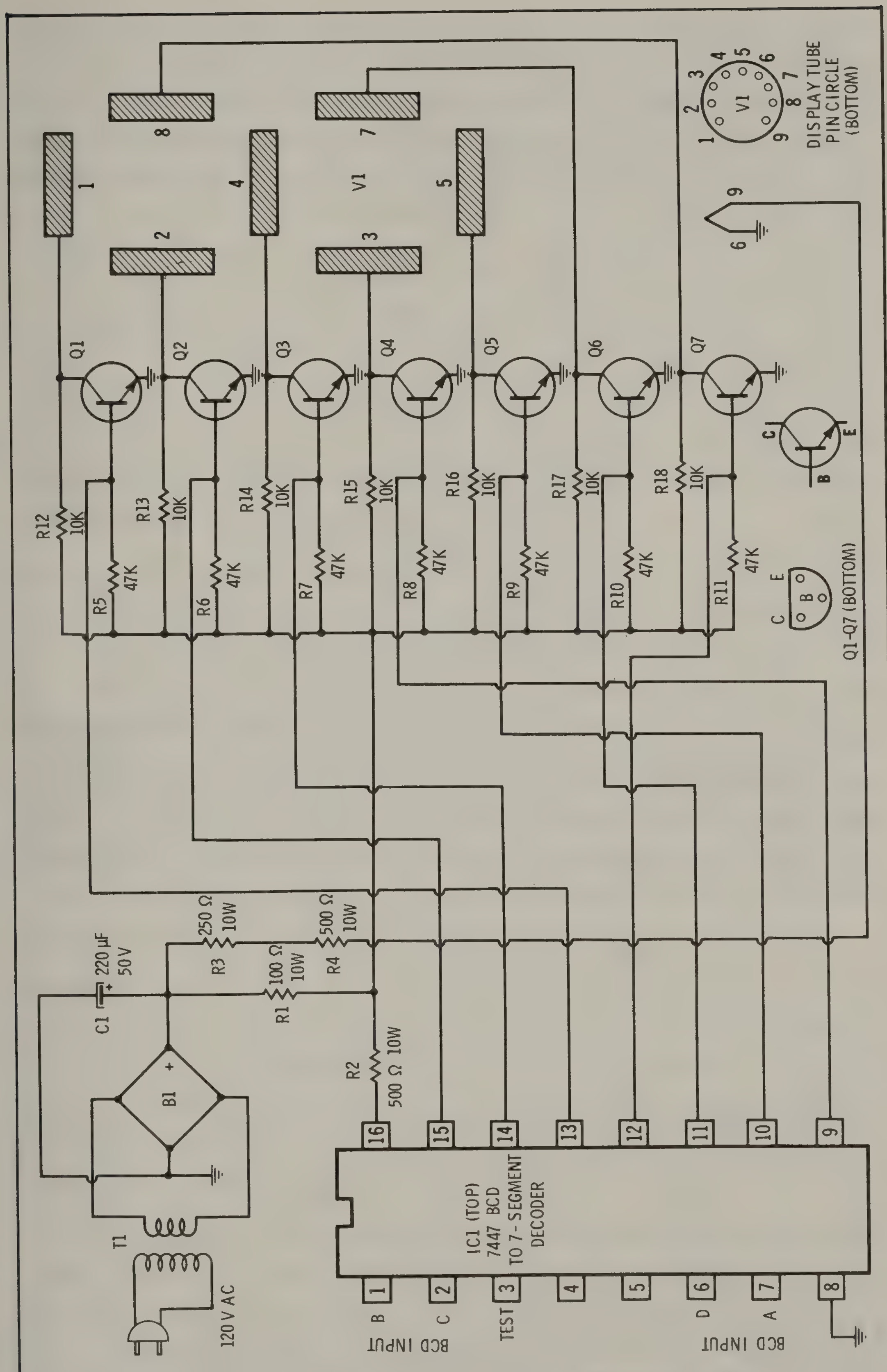


Figure 4-1. BCD to 7-segment decoder/driver and display.

The 7447 is designed so that the binary coded decimal digits corresponding to 0–9 produce the output signals required to form these digits on a 7-segment display device. The binary equivalents for the decimal numbers 0–9 are shown in Table 4-1. Figure 4-2 shows the appearance of a 7-segment display device for each of the decimal digits.

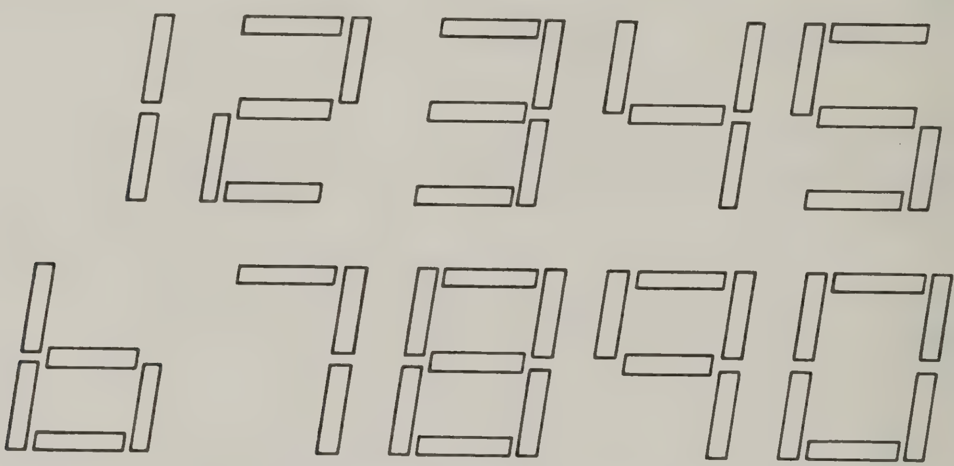


Figure 4-2. Decimal digits in 7-segment format.

From Table 4-1 you can see that any decimal digit from 0 to 9 can be represented by 4 or fewer binary digits, and this is why the 7447 has a 4-position input. The inputs are labeled A, B, C, and D and correspond to the least through most significant digits respectively. The BCD input conditions of the 7447 for each of the decimal digits are also shown in Table 4-1.

Table 4-1. Binary Number System

Decimal	Binary			
	BCD Input			
	D	C	B	A
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

In addition to BCD decoding, the 7447 incorporates several additional functions. The output of the device can be inhibited by means of an appropriate signal at one of the *blanking* pins. This feature is not used here but is useful in electronic calculators and other digital readout devices, since it permits extraneous zeroes preceding or following a number to be automatically blanked out.

The 7447 also incorporates a lamp test feature. By connecting pin 3 to ground, all 7 outputs are activated. If the display device or its driving circuitry is defective, the problem will be immediately evident, since the inoperative segments will not be lighted. It's important to be able to test the display portion of th circuit, since an inoperative segment can cause major readout errors. For example, a non-operating middle segment will cause an 8 to appear as a 0.

Display Tube Drive Circuitry

From our discussion on lamp drivers in Chapter 3, you should recall the operation of this important circuit. Some display devices, particularly those incorporating LEDs, can be driven directly by the 7447, but the higher voltage fluorescent display tube used here requires separate driving transistors for each of the 7 segments. These transistors are Q1–Q7 in Figure 4-1. Many general-purpose NPN switching transistors will operate in the circuit, but the Radio Shack transistor specified here is well suited for the voltage level. Resistors R5–R18 complete the display tube drive circuitry.

Display Tube

The display tube employed in this project is an electrofluorescent type. A relatively recent development, the fluorescent display tube presents a far more pleasant appearance than the older Nixie style neon gas discharge readout. Nixies are a rather unpleasant orange, while the fluorescent tube is a very pleasing blue green.

The tube contains 7 phosphor-coated rectangular metal segments mounted on an insulator. Contacts are attached to each segment and connected to 7 of the 9 pins on the base of the tube. The remaining 2 pins are connected to the filament. In operation, electrons are continuously emitted by the two filament wires (cathode). If a potential is applied to one or more

of the phosphor-coated metal segments (anodes), the electrons from the cathode are attracted to each energized segment. During their passage through the phosphor coating on each anode, the electrons excite some of the phosphor atoms. As the atoms fall back to a lower energy state, they emit photons with the characteristic blue-green wavelength of the fluorescent display tube.

CIRCUIT ASSEMBLY

This project employs more components than most, so try to follow the layout in the pictorial shown in Figure 4-3 for best results. Begin assembly by drilling two $3/16$-inch mounting holes for the power supply transformer in the upper left corner of the perfboard. The holes should be 2 inches apart. Don't install the transformer at this point.

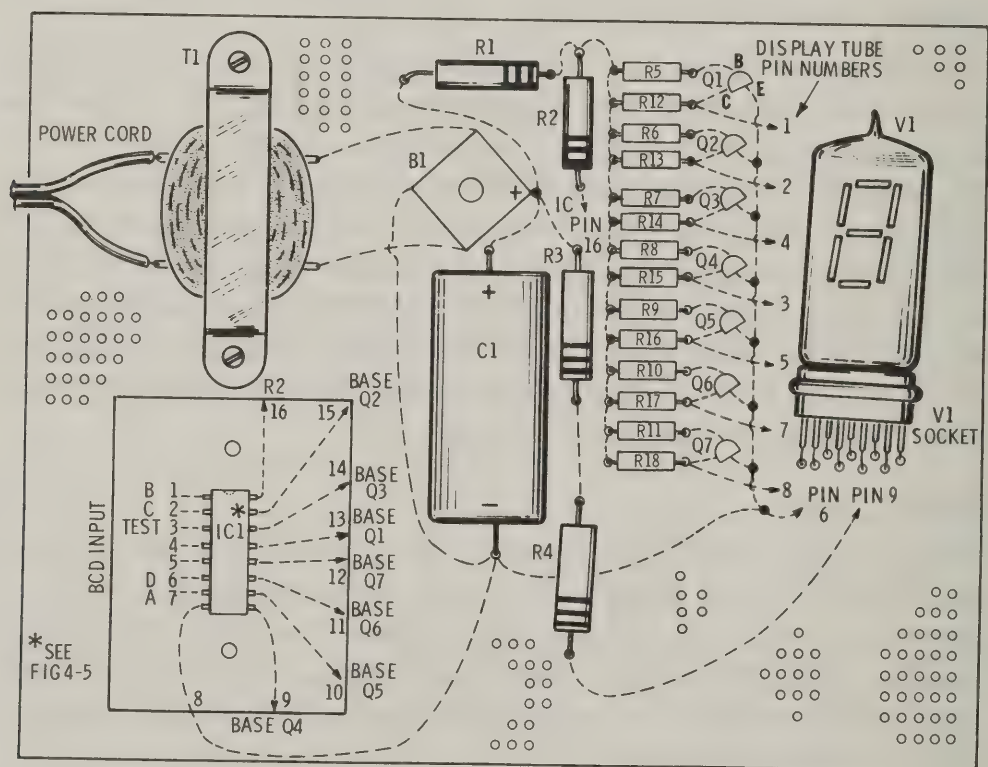


Figure 4-3. BCD to 7-segment decoder and display pictorial.

Next, install resistors R5–R18 in a row as shown in Figure 4-3. Bend the leads of each resistor outward to hold them in place. Then, run a 3-inch length of bare wire under the leads of all 14 resistors nearest the transformer mounting holes.

Solder each lead to this wire and clip the excess lead length from each resistor.

The transistors are installed next. First, make sure you are familiar with the lead designations of the transistors (Figure 4-1), and then install Q1 as shown in Figure 4-4. Solder Q1's base to R5's (47,000 ohms; yellow violet orange) remaining lead and Q1's collector to R12's (10,000 ohms; brown black orange) remaining lead. Leave Q1's emitter lead alone for now; we'll get back to it shortly.

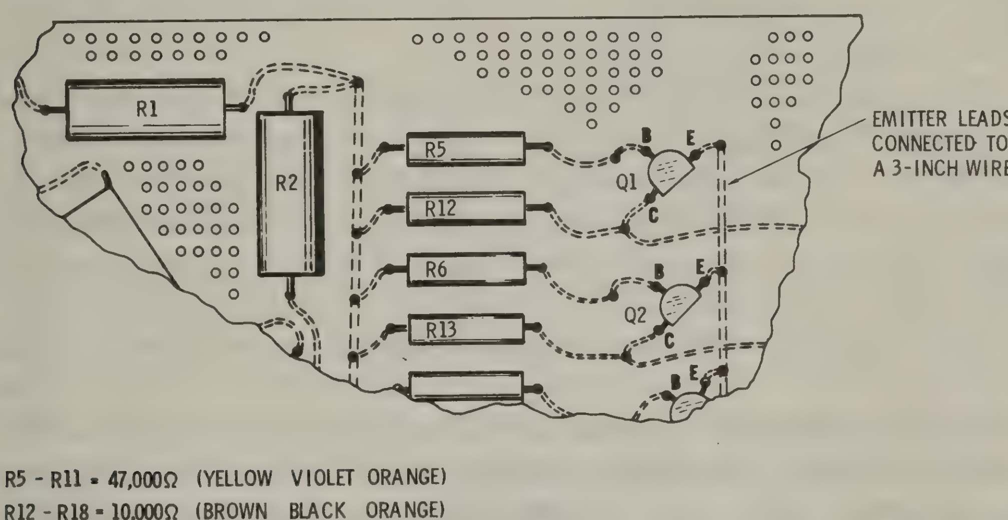


Figure 4-4. Detail of Q1, R5, and R12.

When Q1 is soldered in place, look it over to make sure you're satisfied with the appearance and orientation of the connections. If it doesn't match the pictorial detail shown in Figure 4-4, remove it and try again. It's must easier to remove and reinstall just Q1 than all 7 transistors later.

When you are satisfied that Q1 matches the detailed pictorial in Figure 4-4, install and solder the base and collector leads of transistors Q2–Q7 one at a time. When all the transistors are in place, bend all the emitter leads outward and place a single 3-inch length of bare wire under the emitter leads (Figure 4-4). Solder the wire to each lead, beginning with Q1. Clip all excess lead lengths, and you've completed assembly of the display tube drive circuitry.

Next, install the power-supply components onto the perfboard, as shown in Figure 4-3, and solder them into place. R1 and R2 are mounted adjacent to the drive circuit resistors and at a right angle to one another. R3 and R4 should be installed

directly below R2 so that the three resistors form a straight line.

Be sure to use 10-watt resistors for R1–R4. These resistors become pretty warm in operation, and a lower rating will result in a burned-out resistor.

When you install the rectifier bridge module, make sure the lead nearest the plus (+) mark points directly away from the transformer mounting holes. See Figure 4-3 for details. Also make sure the positive (+) end of C1 is soldered to the plus lead on the rectifier. The capacitor will be damaged if its leads are reversed.

When all the power-supply components are in place, solder a length of insulated hookup wire from the bare wire connecting all the display tube drive resistors to the junction of R1 and R2. Then solder another length of insulated hookup wire from the bare wire connecting all the transistor emitters to the negative terminal of C1. From now on, this connection will be called the *ground*, and several other leads will be soldered to it later.

By now you have installed almost all the components on the perfboard, and only three remain, the display tube, IC, and transformer. The tube is next. Remove the metal mounting rim from the 9-pin miniature tube socket with a pair of diagonal cutters. Then solder a 3½-inch length of insulated hookup wire to each of its 9 terminals. Thread the wires through the perfboard holes as shown in Figure 4-3, making sure that the face of the display tube will face outward when it is installed in the socket. Each of the terminals on the socket is numbered, and it is properly installed on the board when the wide space between the terminals numbered 1 and 9 are closest to the perfboard.

Using care to prevent mistakes, connect each of the 7 anode leads to their respective connection points at the junction of each transistor's collector and the 10,000-ohm resistor. Use the wiring guide in Table 4-2 to make sure you make no errors, and double check your work with Figures 4-1 and 4-3. You can improve the appearance of the wiring connections by trimming each socket lead so that it reaches its connection point with about half an inch overlap. When you have completed soldering the 7 leads in place, the wiring will neatly fan out from the socket area to each transistor lead.

Complete the wiring of the socket by soldering terminal 6 to the ground connection and terminal 9 to the remaining lead of R4. For neatness, trim the leads to the correct length before soldering them in place.

Table 4-2. Display Tube Wiring Guide

Pin Number	Connection Point
1	Collector Q1
2	Collector Q2
3	Collector Q4
4	Collector Q3
5	Collector Q5
6	Ground terminal
7	Collector Q6
8	Collector Q7
9	R4

We'll insert the display tube in the socket shortly, but first let's install the IC. I soldered the IC directly to a socket adaptor board, but you can solder an IC socket to the board first if you prefer. Be sure to use a 16-pin socket (Radio Shack 276-030). When you have soldered the socket or IC to the adaptor, connect 4½-inch lengths of hookup wire to each solder pad. Install the completed board in the main perfboard by threading the 16 leads through a rectangular outline of holes. Let the IC board stand off the perfboard about half an inch so that you can reach the solder pads with a soldering iron, if necessary.

With the IC mounting board in place, begin soldering the various leads in place as shown in Figure 4-5. You can make the wiring much neater by cutting each connection wire to the length needed to reach its connection point. Count the leads from the IC soldered to connection points when you are finished. You should count 9 of them. Leave the remaining leads alone for now.

Conclude assembly of the circuit by installing the transformer in its two mounting holes with appropriate hardware. I used ¼-inch, 6-32 screws and nuts, but use any hardware that's handy and will secure the transformer rigidly in place. Note that the side of the transformer labeled PRI 120 V AC faces *away* from the main part of the board. The primary terminals are located on this side of the transformer.

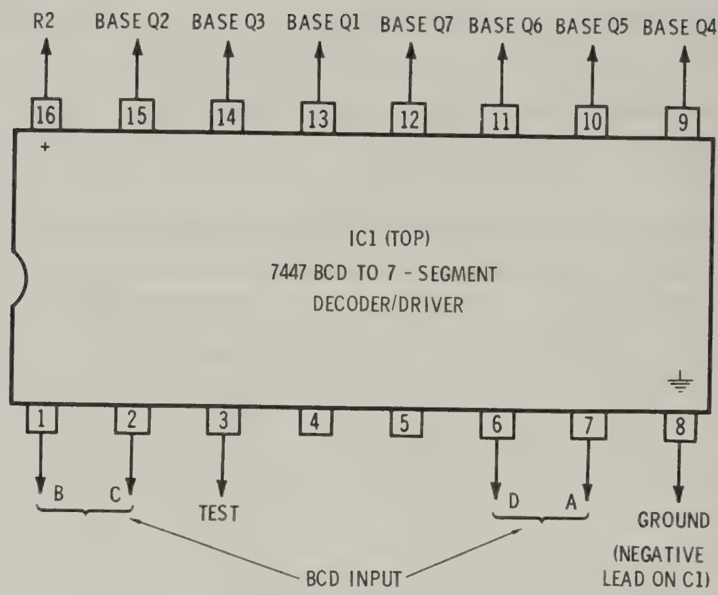


Figure 4-5. BCD decoder IC wiring diagram.

When the transformer is in place, connect the two leads on the rectifier module to each of the secondary terminals. If you follow the layout I used, the leads should just reach the terminals if they are bent under the perfboard and passed back out the holes directly adjacent to the terminals. If they don't, use some short lengths of insulated hookup wire to bridge the gap.

Solder a power cord to the two primary terminals on the transformer. When the connections have cooled, carefully insulate the terminals with black electrical tape. Be sure to insulate the terminals carefully, or you may receive a dangerous electrical shock when operating the circuit.

When the circuit is complete, install the display tube in its socket. The project is now ready for testing, and it should resemble the prototype shown in Figure 4-6.

TESTING AND OPERATION

Very carefully inspect the completed project for possible wiring errors before connecting the power cord to a source of household current. Start with the power-supply components, and work through the segment drive circuitry. Check all the display tube connections, and trace all the IC connection leads. Make sure all connections have been made. (For example, make

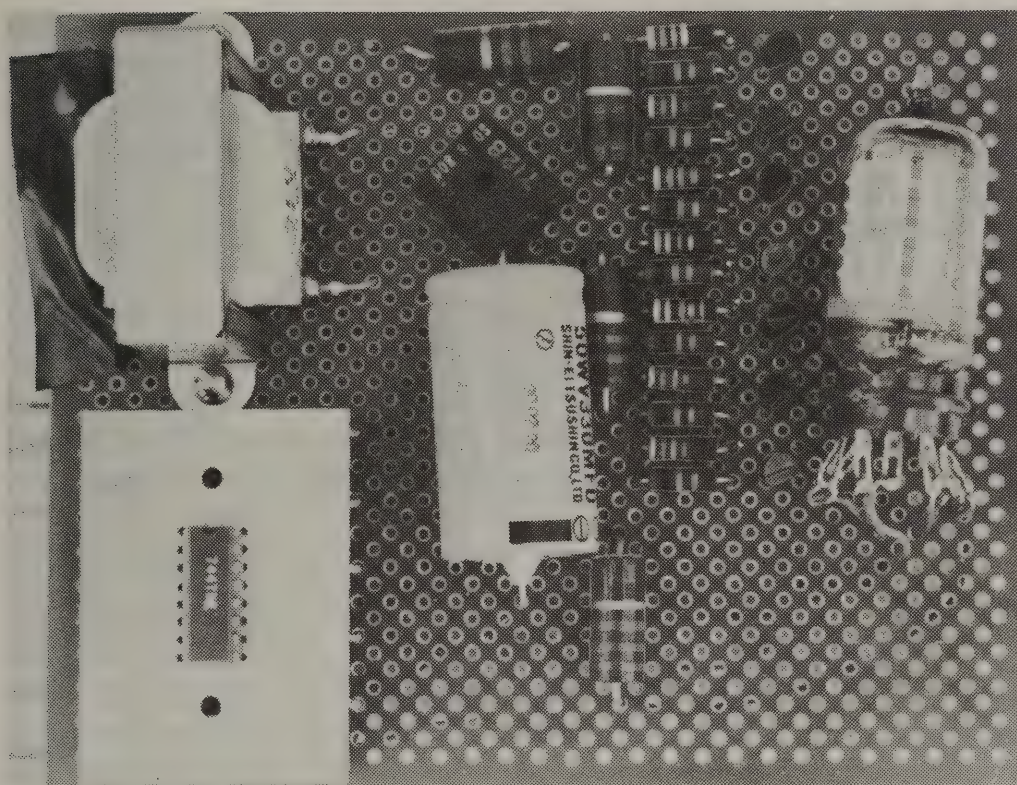


Figure 4-6. Assembled decoder/driver and display.

sure you did not forget the connection from the transistor emitters to ground.) Also, make sure there are no short circuits or bare wires very close to one another. If you used insulated hookup wire, this should be no problem. Finally, remove any wire clippings and solder fragments that may be hidden under the wiring or components.

Prepare for the operating test by connecting a clip lead from the IC's pin 3 connection lead to the ground connection. When you are absolutely sure all wiring connections are correct, plug the power cord into a source of 120 volts and watch the display tube. After a few seconds, the tube should form an "8." If nothing happens, quickly unplug the power cord and repeat the wiring check. This time use care in inspecting every single connection. If the solder connections look suspicious, reheat them with a soldering iron and let them cool without any movement. Check the IC mounting board. Have any of the connection leads become unsoldered?

If one or two display tube segments fail to light, you can troubleshoot the problem with a voltmeter. First, determine which drive transistors are connected to the inoperative seg-

ments. With the negative probe from the meter connected to the ground connection and the positive probe touching the transistors collector lead, you should get a reading of about 22 volts. If so, touch the probe to the display tube socket terminal corresponding to the bad segment. If you don't get a voltage reading, resolder the connections between the transistor and socket. If you do, unplug the tube and clean the tube socket and tube pins with a solvent. Unless the tube has a bad segment, the display should now operate normally. If a segment is still inoperative, work backwards through the driving transistor connections to the IC. Resolder all connections, including the associated resistors. If this fails to cure the problem, replace the transistor.

You can check the old transistor with an ohmmeter after removing it from the circuit. The meter should show a very high resistance when the negative probe is touched to the base lead and the positive probe to either of the other leads. The resistance should be much lower when the positive probe is connected to the base and the negative probe to either of the other leads. If you get readings which are different from these, discard the transistor.

I seriously doubt that you'll have to employ all these troubleshooting techniques with your project, but at least now you know more about troubleshooting digital circuits. To get some experience at troubleshooting in the event your project works properly the first time, you may want to get a friend to sabotage one of the drive transistors or a connection by clipping a single lead. Then you can follow through the procedures outlined above to pinpoint the trouble. With a little practice, you can troubleshoot the circuit and repair the problem in a matter of minutes. In fact, troubleshooting straightforward digital circuits like this one is much easier than repairing most radios.

When the circuit is operating properly, you can use it to convert binary inputs into the decimal digits 0–9. The "8" formed during your initial test was not actually the digit 8 but a test procedure provided by the decoder IC to make sure all 7 segments on the display tube activate. To operate the device, try an easy binary number like 0001 (decimal 1). Referring to the information in Table 4-1, you'll see that the IC's input terminals marked D, C, and B (pins 6, 2, and 1) must be at the "0" or "low" binary state to give a "1" on the display tube. To ful-

fill this requirement, simply touch these three leads together and connect them to ground with a clip lead. A "1" should appear on the display tube. To get a "0," *all* the BCD inputs must be low; so touch the remaining input lead (pin 7) to ground and a "0" will appear. To get a "7," touch only the D input (pin 6) to ground. You should be able to generate the decimal digits 0–9 by appropriate connections from the four BCD inputs to ground.

Now that you've actually tried converting binary numbers into decimal output, the truth table in Table 4-1 probably makes much more sense. At least now you can figure out how the name "truth table" originated.

GOING FURTHER

You can make a permanent BCD to decimal demonstrator unit by connecting a toggle switch from each of the BCD inputs to ground. The switches should be arranged in a D, C, B, A order and labeled. You can also connect push-button switches from the lamp test connection (pin 3) and the blanking output (pin 4) to ground. When the lamp test switch is pressed, all 7 segments of the display tube should be illuminated. When the blanking switch is pressed, all 7 segments should be extin-

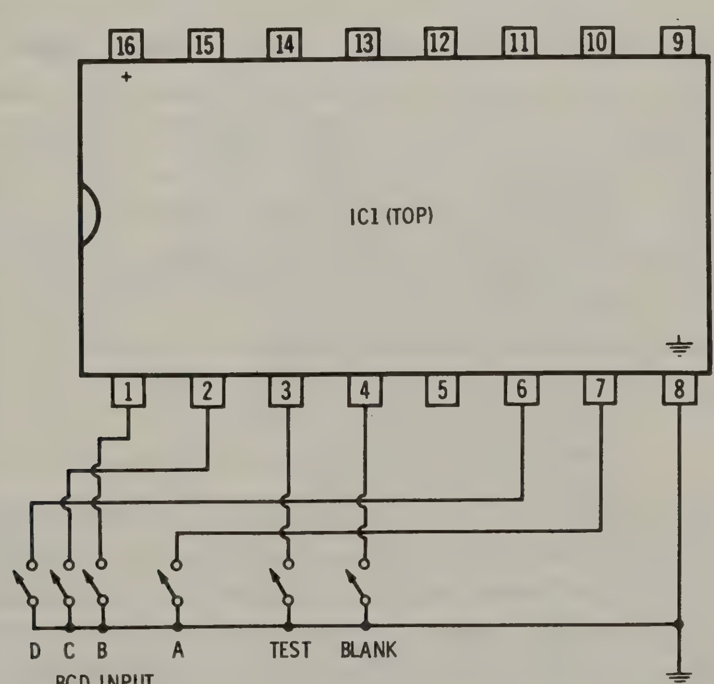


Figure 4-7. Switch circuit for manual BCD input.

guished. These actions should occur no matter what binary number is entered into the decoder's BCD input. Figure 4-7 shows the various connections required to connect all six switches.

You can use a voltmeter to check the state of the various drive transistors during operation. Connect the meter's negative probe to the ground connection and use the positive probe to make contact with the collector of each transistor. You'll find that some transistor collectors show a reading of about 22 volts, while others show no voltage. Only the transistors connected to a lighted segment in the display tube will show a voltage.

If the display tube segments are not evenly illuminated, you can increase the tube's brightness by reducing the value of R3 slightly. If the filaments in the tube glow visibly orange, increase R3 slightly to reduce the filament voltage and prolong the tube's life. You can perform these adjustments very quickly by removing R3 and connecting a 5000-ohm potentiometer in its place with clip leads. Connect the clip leads to the center terminal and one of the two outer terminals. Adjust the potentiometer until the tube is operating properly and disconnect it from the circuit; measure its resistance with a VOM and substitute a 10-watt resistor with a similar value.

Table 4-3. BCD Decoder and Display Parts List

Item	Description
B1	Module, rectifier bridge (276-1146)
C1	Capacitor, 220 μF, 50 volt (272-1045)
IC1	7447 Decoder, BCD to 7-segment (276-1805)
Q1-Q7	Transistors, NPN, switching (276-2016)
R1	Resistor, 100 ohm, 10 watt
R2	Resistor, 500 ohm, 10 watt
R3	Resistor, 250 ohm, 10 watt
R4	Resistor, 500 ohm, 10 watt
R5-R11	Resistors, 47,000 ohm
R12-R18	Resistors, 10,000 ohm
T1	Transformer, 120 V AC/24 V AC (273-1386)
V1	Fluorescent display tube, 7-segment (276-049)
Misc	Perforated board (276-1392), IC socket adaptor (276-024), 9-pin tube socket (274-1512), power cord (278-1255), electrical tape, hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

CHAPTER 5

DIGITAL COUNTING CIRCUIT

In Chapter 2, you saw how the binary number system enables a digital circuit, such as a flip-flop, to count. In Chapter 4, I showed you how to convert the awkward binary numbers into their decimal equivalents using a 7447 decoder/driver IC and a display tube.

You could connect a string of flip-flops like the 923 together, making a digital counting circuit which would add succeeding input pulses or signals and display a running total on the readout project described in Chapter 4. But working with four individual ICs is complicated, since each unit has eight leads. Fortunately, there is an IC available which already incorporates four individual flip-flops. It's the 7490 decade counter and is available from Radio Shack. Like the 7447 decoder in the previous project, the 7490 is a sophisticated IC containing some 84 transistors, 24 diodes, and 76 resistors.

In this project, you'll supplement the basic BCD to 7-segment decoder of Chapter 4 with an automatic counting circuit, making use of the decade counter and a simple pulse generator. Besides learning quite a bit more about the operation of digital logic circuits, you will be able to find some practical uses for the completed counter.

HOW IT WORKS

Operation of the counter is dependent on the binary counting action of a string of flip-flops. Since the 7490 has only 4 flip-flops, it is limited to 4 binary digits. But that's all we need for the BCD equivalents of the decimal digits 0–9. For higher numbers, a second unit can be activated each time the first one reaches "0." In this way decimal counting can be achieved with one decade counter per digit.

The circuit described here has but one 7490, but that's all we need to demonstrate the basics of a binary counter. In operation, a simple unijunction transistor (UJT) oscillator supplies a continual series of pulses to the input terminal (pin 14). You can see how the unijunction oscillator operates by referring to the circuit diagram in Figure 5-1. Capacitor C1 is charged through resistors R1 and R2 until Q1's emitter is forward biased. At this point, the UJT (Q1) conducts and permits C1 to discharge through Q1, R4, and R5. When C1 discharges,

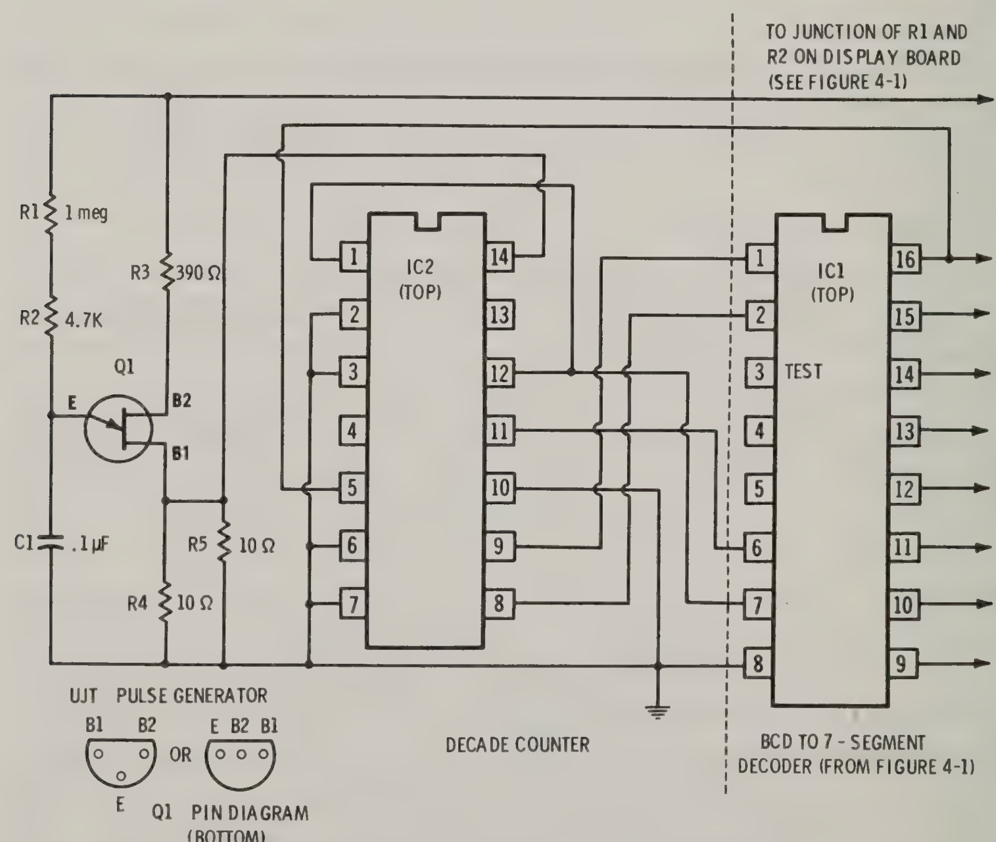


Figure 5-1. Pulse generator and decade counter circuit.

the UJT is again turned off, and C1 begins charging again until the cycle repeats.

The discharge of C1 is very fast and appears as a voltage spike across R4 and R5. Both R4 and R5 are required to reduce the amplitude of this spike somewhat. The repetition rate of the oscillator can be changed by altering the value of C1 or R1. We'll discuss this topic more in the section on "Going Further."

In reference to Figure 5-1, the pulses from the UJT oscillator are fed into the input of the decade counter. Each incoming pulse initiates a binary counting sequence as each of the 7490's four internal flip-flops alternately change state. Since each flip-flop is connected to an output pin, it's possible to check the status of all the flip-flops by simply connecting a voltmeter across each output pin and ground. You can even use an LED. Just use a clip lead to connect its cathode to ground and touch its anode lead directly to each of the four output pins on the 7490 one at a time.

As shown in Figure 5-1, each of the 7490's BCD outputs are connected directly to the corresponding BCD inputs of the 7447 decoder/driver. This causes the 7447 to automatically convert the binary count from the decade counter into decimal digits, which can be seen on the readout tube. The result is a continuous 0–9 counting sequence displayed on the tube. Each time the count reaches 9, it recycles to 0 and continues. With another counter circuit, you could feed a carry pulse from the 7490 into a second counter to count to 99. Three circuits would give 999; four, 9999; and so forth.

You can get a better idea of the counting action of the complete circuit by referring to Figure 5-2. The diagram in the figure is called a *timing diagram,* and it shows the output state

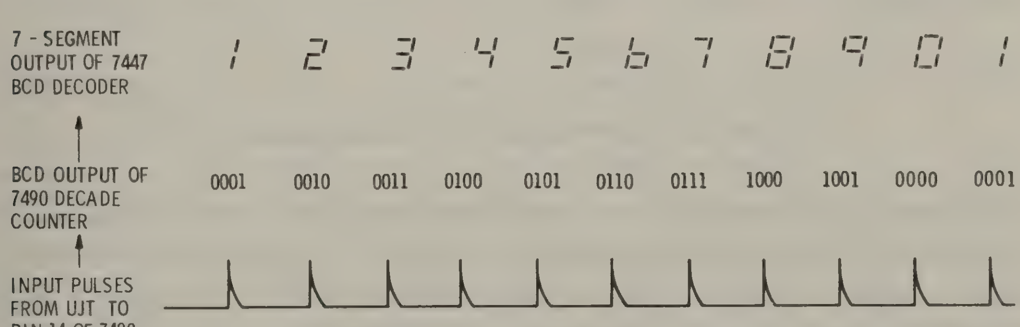


Figure 5-2. Digital counting circuit timing diagram.

of both the 7490 and 7447 after each incoming pulse. The output of the 7490 is particularly interesting, since you can see how the binary numbers indicate the state of each of its four flip-flops.

We'll discuss some additional operating features of the counting circuit later, but first let's see how to put it together.

CIRCUIT ASSEMBLY

I assembled the prototype decade counter and pulse generator directly to the perfboard of the already constructed BCD to 7-segment decoder circuit, but you can use a separate board if you prefer. Assemble the UJT oscillator first by referring to the pictorial in Figure 5-3. Compare Q1 with the base diagram

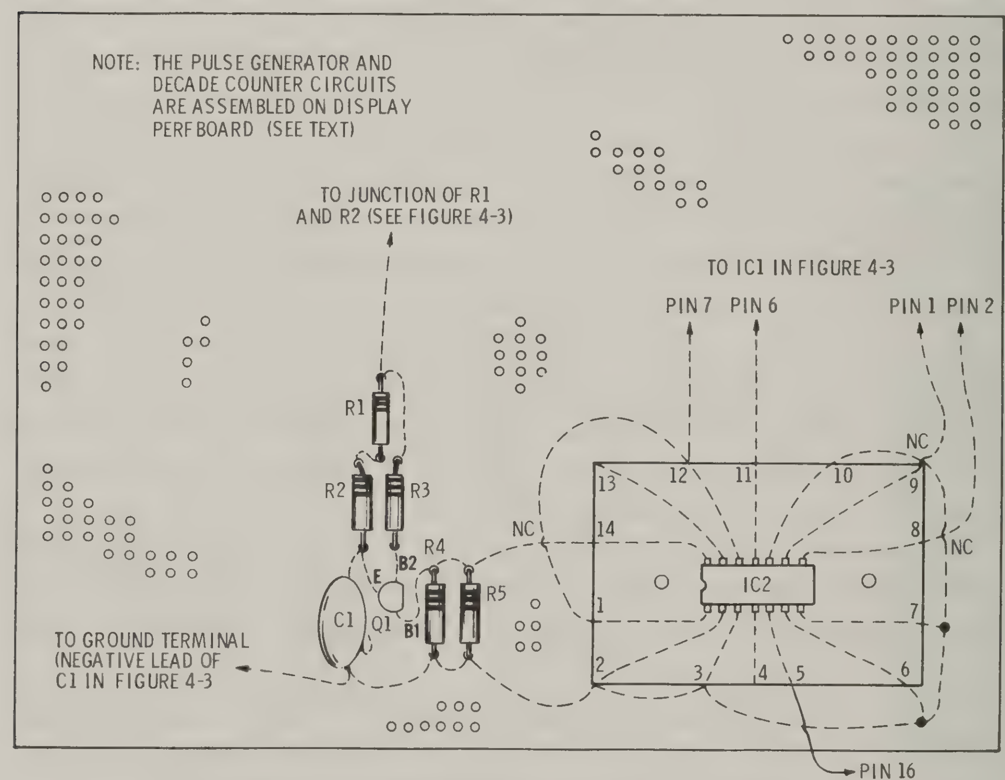


Figure 5-3. Parts layout for decade counter.

in Figure 5-1 to make sure you know the identity of each lead; then install Q1 in the perfboard. Insert C1 in the board also, and solder one of its leads to Q1's emitter. Next, install R1 and R2 and solder them to one another. Solder R2's remaining lead to Q1's emitter.

R3 is next; insert it into the board next to R2 and solder its upper lead to R1 and its lower lead to Q1's B2 lead. Continue assembly of the oscillator by installing R4 and R5 and soldering their leads to one another. Then solder C1's remaining lead to the lower junction of R4 and R5. The upper junction of R4 and R5 is soldered to Q2's B1 lead.

Complete assembly of the oscillator by connecting an insulated length of hookup wire from the junction of R1 and R3 to the junction of power-supply resistors R1 and R2 in Figure 4-1. This will provide about 25 volts for the operation of the oscillator. Connect a second length of insulated hookup wire from the junction of the oscillator's C1, R4, and R5 to the ground connection of the decoder circuit (the negative lead of C1 in Figure 4-1). Be sure to clip off all excess lead lengths. When the oscillator is completed, prepare the 7490 IC for installation. Like the 7447 in the decoder circuit, I simply soldered the 7490 directly to a socket adaptor board, but you can solder a socket to the adaptor or use a socket alone if you prefer. When the IC or socket is soldered in place, solder a length of insulated hookup wire between the solder pads which connect to the IC's pins 1 and 12. Solder another insulated hookup wire from pins 6 and 7 to pin 10. Then solder a length of insulated hookup wire across the solder pads from pads 2 and 3 to pad 6. Next, solder 6-inch lengths of insulated hookup wire to the solder pads which connect to the IC's pins 2, 8, 9, 11, 12, and 14.

When all the connection leads have been soldered to the 7490's adaptor board, carefully inspect the assembly to make sure all the leads are soldered correctly. I find it helpful to mark the IC's pin numbers on or adjacent to the respective solder pads. Complete final assembly of the decade counter by threading the IC connection leads through holes in the decoder's perfboard. The mounting board should stand about half an inch above the perfboard. The space between perfboard and IC will give you some room if it becomes necessary to solder a new connection lead to the 7490 or replace an existing one.

Fig. 5-4 shows the connection points for each of the 7490's leads. For a neat appearance, be sure to trim the leads so they overlap the intended connection point by about half an inch.

If you followed the parts layout shown in Fig. 5-3, the completed counting unit should resemble the prototype unit shown in Fig. 5-5. The BCD to 7-segment decoder/driver project

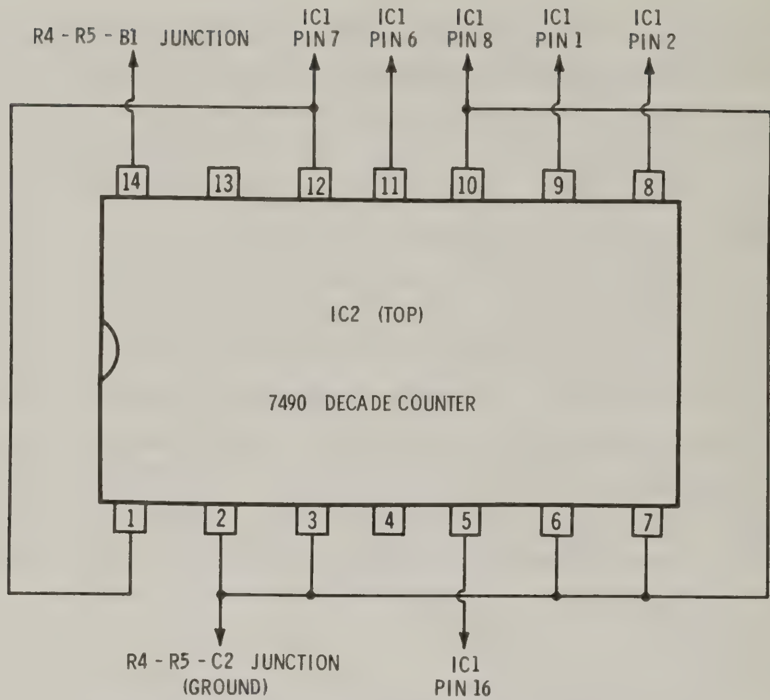


Figure 5-4. Decade counter IC wiring diagram.

leaves ample space for inserting all the parts for the counter circuitry.

TESTING AND OPERATION

As with any semiconductor project, carefully check all wiring connections for possible errors before connecting a power source. Be sure to remove any wire clippings and solder scraps also.

When you are satisfied that the circuitry is properly assembled, plug the power cord into a source of house current and watch the display tube. It should display a 0–9 counting sequency as soon as the tube's filaments are warm. The cycle will continuously repeat itself. If the tube fails to show a count, or if one or more segments fail to light, recheck all the wiring after disconnecting the power cord. No counting sequence probably means the UJT oscillator isn't operating properly, while irregular segment displays or count sequences probably mean an error in the connections to the 7490.

Note that the reset lead connected to pins 2 and 3 on the 7490 *must* be grounded or the display will not operate. The reset connection permits the display tube to be reset to "0" any time

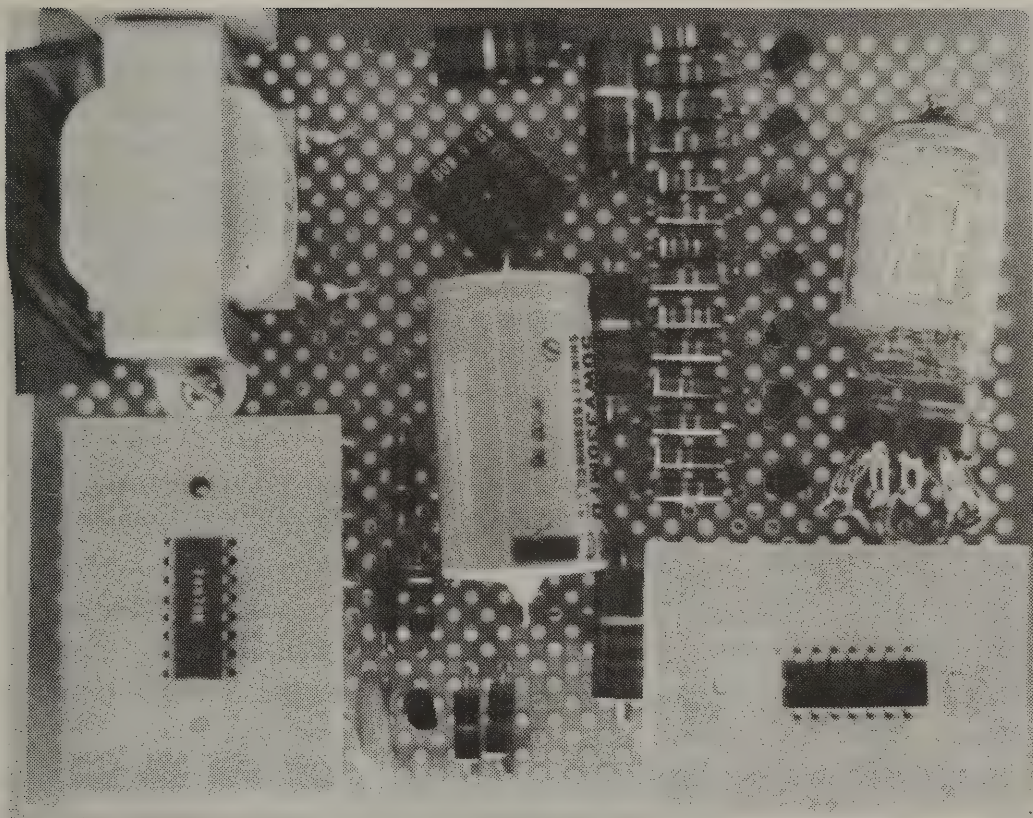


Figure 5-5. Assembled decade counter.

in the count cycle. If the input lead (pin 14) is disconnected from the UJT oscillator, the tube will stop counting and continuously display the last digit counted. This illustrates the use of the flip-flop as a memory element. As we saw in Chapter 2, a single flip-flop will store either a binary "0" or "1." This circuit shows how a string of four flip-flops will store the binary equivalents for each of the decimal digits 0–9.

GOING FURTHER

You can try several interesting experiments with the completed counter circuit. If you tire of watching the tube display a 0–9 continuous count at a constant rate, it's easy to speed it up or slow it down by simply changing the pulse rate of the UJT oscillator. This can be done by changing the value of C2, but a better and more efficient way is to remove R1 and replace it with a 2-megohm (2,000,000-ohm) potentiometer, such as the Radio Shack 271-093. Connect the center terminal of the pot to R2 (open the R1, R2 connection) and one of the end ter-

minals to R3. Now you can rotate the pot's shaft to vary the counting rate from a count every second or so to a blur far too fast for the human eye to distinguish. In fact, at count rates faster than about 20 pulses per second, all the segments will appear lighted and the display tube will show what appears to be the digit "8." Actually, the tube is displaying all the digits 0–9 in rapid sequence.

For a super-slow count rate, just connect a fairly large capacitor across C2's terminals. With a 1,000,000-ohm resistor for R1 and a 2-μF capacitor across C2, you will get a rate of about one count every 5 seconds.

The counting action of the completed circuit suggests an important application: a digital clock. Actually, the circuit is a kind of clock, and its operation is very similar to more sophisticated units. High-quality digital clocks use a high-frequency crystal oscillator as a timing source. A chain of flip-flops is used to divide the high-frequency rate of pulses into a slower format capable of being displayed. Since quartz crystals have very precision oscillation characteristics, quartz clocks can have a very high degree of accuracy.

Your unijunction oscillator isn't nearly as accurate as more sophisticated time measuring devices, but you can use the counter as a special-purpose "clock" for darkroom roles and other applications requiring relatively brief timing intervals. You can calibrate the device by means of the potentiometer soldered in the circuit in place of R1.

Another application for the counter is as a random number generator. Best results will be obtained by leaving the potentiometer used in the clock experiment in place. Adjust the pot until the counting rate becomes a blur on the display tube. Then stop the pulses from the UJT oscillator by temporarily bypassing C1 of the oscillator with a clip lead. The display tube will then indicate the count being registered when the oscillator was disabled. Since the pulse rate is so fast, there is no obvious way of predicting which number is on the tube when the incoming pulses are stopped; so the counter is essentially a random number generator or a ten-sided electronic die.

To make the random number generator more practical, disconnect the connection lead from the pulse output of the UJT oscillator (the one connected to the UJT's B1 and the junction of resistors R4 and R5) to the input of the 7490 IC (pin 14).

Then connect a SPST toggle switch, such as the Radio Shack 275-011, between the oscillator pulse output and the IC. With the switch in the On position, the counter will operate as normal; but when the switch is turned to Off, the count will stop, and the readout tube will display the last number registered in the count sequence.

The switch is not very large, and with a little care you should be able to mount it in a small space on the perfboard. A ½-inch hole will be required for mounting, and you may have to rearrange some of the connection wires that are located on the back of the board.

As I noted earlier, the ability of the counter circuit to display and hold a digit after the counting sequence is stopped illustrates the memory or storage role of a string of flip-flops. Flip-flops are too complicated for use in most large-scale memory applications, but they are very handy as temporary storage registers. Sometimes flip-flop registers are referred to as electronic "scratch pads." They can also be used as "read-write" memories, since a signal can be fed in and read out without changing the state of any of the flip-flops.

Flip-flop memories are *volatile*. That is, they retain stored information only so long as they are supplied with operating power. Once the power is shut off, the memory resets and automatically clears itself. Does this suggest a simple way to clear a flip-flop circuit such as the decade counter?

An interesting variation of the ten-digit electronic die we were discussing a few paragraphs ago employs the blanking capability of the 7447 BCD decoder (IC). All that's necessary is to use a DPDT switch, such as the Radio Shack 275-1546, in place of the SPST switch used above. Connect the UJT oscillator and pin 14 of the 7490 (IC2) to one side of the switch (Figure 5-6). Then, use lengths of connection wire to connect pin 4 and ground to the other side of the switch.

When the switch is in the "on" position, the oscillator will send a rapid sequence of pulses into the 7490 IC. But since pin 4 of the 7447 IC is grounded, the display tube will be blanked out and no digits will appear. When the switch is turned to the Off position, the oscillator will be disconnected from the decade counter, and the display tube will no longer be blanked out. Using this simple technique, your electronic random number generator will appear much more sophisticated.

There are several other experiments you can try with the counter circuit. For example, there's no need to use the UJT oscillator to provide input pulses. You can disconnect or even omit the oscillator and feed the pulses in yourself by connecting a SPST push-button switch from the input of the 7490 (pin 14) to any other source of positive voltage. The 7490 requires a minimum of 2 volts to count an input pulse. Don't exceed 5.5 volts on the input or the IC may be damaged.

As you can see by now, a simple digital counting and display circuit has a wide variety of uses. By connecting additional decade counters and display tubes to the first, you can count to any number up to the maximum number of digit places.

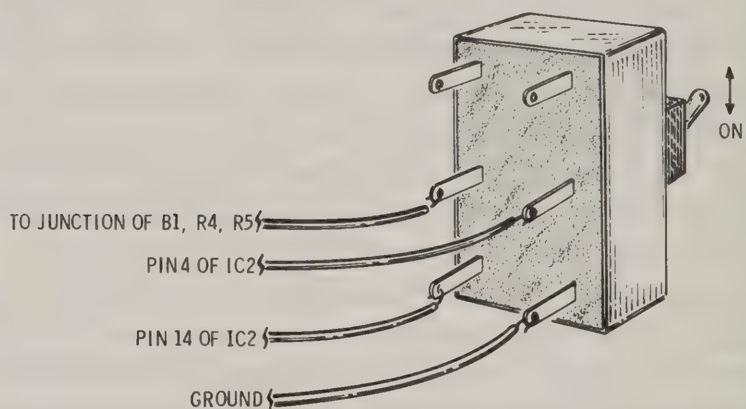


Figure 5-6. Wiring a DPDT switch to utilize IC2's blanking capability.

The basic counter and decoder described here looks fairly complicated because of all the parts required to drive the segments of the display tube. Of course the circuitry inside the ICs is amazingly complicated, but take away the driving circuitry, replace the power-supply parts with a 6-volt battery, and you're left with the ICs, UJT oscillator, and display tube. The tube we're using requires the drive circuitry because of its high operating voltage, but light-emitting diode readouts can be driven directly by the 7447, with nothing but a single series dropping resistor between each of the segments and the 7447.

There are even ingenious techniques for using one 7447 to drive a string of perhaps eight digital displays. Most portable electronic calculators use one of these methods to reduce both cost and size. The most common way to use a single 7447 to drive several displays is called *strobing* or *multiplexing*. A

pulse generator, called a clock, causes a single 7447 to be connected to each display in rapid sequence. Since the human eye cannot detect a flicker rate faster than about 18 or 20 flashes per second, a sufficiently fast strobe rate causes all the digits to appear on at the same time, when actually only one digit is on at any one instant.

If the subject of digital logic, counters, displays, and decoders interests you as much as it does me, I suggest you visit a library to read up on the subject in more detail in one of the many good books on digital electronics. But first, let's try another project and see how a common digital IC can be used in some very different roles.

Table 5-1. Pulse Generator and Decade Counter Parts List

Items	Description
C1	Capacitor, 0.1 μF (272-1069)
IC1	7490 decade counter (276-1808)
Q1	Unijunction transistor (276-111)
R1	Resistor 1,000,000 ohm
R2	Resistor, 4700 ohm
R3	Resistor, 390 ohm
R4, R5	Resistors, 10 ohm
Misc	IC socket adaptor (276-024), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

CHAPTER 6

DIGITAL IC OSCILLATOR

In Chapter 2, we briefly discussed several digital logic circuits other than the flip-flop. Two of the most basic logic circuits are the AND and NAND gates. An AND gate usually has two input terminals—a simultaneous voltage at both inputs is required to give an output voltage. "No voltage," or a voltage at only one input results in "no output." A NAND gate is simply an AND gate followed by an inverter; its operation is exactly the opposite of the AND gate. It gives an output voltage, unless an input voltage is present on both inputs; then it gives no output.

Gates are very useful as basic "decision" mechanisms in digital logic circuits. In a typical application, a gate is used to monitor the status of two separate circuits, both of which must have completed processing an input signal before the signal can continue passing through the circuitry. Only when the gate receives a pulse at both inputs will it permit the signal to pass on to the next stage of circuitry.

If you assembled the digital readout project in Chapter 3, you have already worked with several kinds of gates. But since the gates were all nicely preassembled into the 7447 decoder/driver IC, you didn't have to connect them yourself.

In this chapter, you're going to get a chance to experiment with some unusual and very useful properties of gates. The project described here uses a low-cost RTL 914 dual 2-input

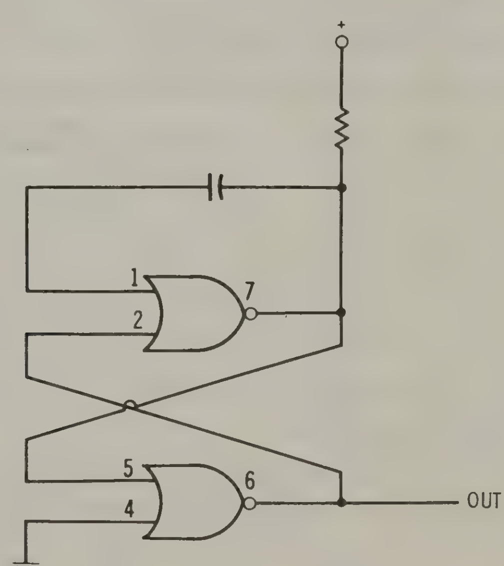
gate. First, we'll build an oscillator using the 914, and in the next chapter I'll show you how to use the 914 for some even more interesting applications.

HOW IT WORKS

The circuitry inside the 914 is simpler than that of most of the ICs we've used so far. Each of the two gates incorporates 2 transistors and 3 resistors for a total count of only 10 components.

By crisscrossing the output of each of the 914's two gates with each other's inputs, it's possible to convert the 914 into a type of flip-flop. To see how this is done, refer to the block diagram in Figure 6-1. Even without a knowledge of what components are in each gate, you can see how the output of each gate is coupled back to the input of the other. This sets up a situation where the output of one gate can directly control the state of the other.

Figure 6-1. The 914 oscillator logic diagram.



The capacitor controls the switching rate of the circuit. When one gate has been on for a time determined by the capacitor, it shoots a pulse over to the other gate and the process repeats itself. A small-value capacitor gives a fast switching rate and a larger one a slow rate. The result is a series of pulses whose frequency can be easily altered by means of the capacitor.

As you will recall from Chapter 2, flip-flops require an external trigger pulse to cause the device to change state. For this reason, a flip-flop is sometimes called a *bistable* circuit. A flip-flop is also called a *multivibrator,* since it is a two-stage amplifier with positive feedback. Putting these definitions together gives us the term *bistable multivibrator,* a complicated way of saying flip-flop.

The flip-flop made by connecting the two gates inside a 914 to one another is unique in that it switches back and forth on its own, without the need for an external trigger pulse. For this reason, its more correct to refer to the circuit as a free-running or *astable multivibrator.* Since the circuit switches back and forth on its own, there's obviously no way to use it as a memory element or for any of the other logic applications of ordinary bistable flip-flops. In fact, the 914 connected as an astable multivibrator isn't a digital logic circuit. It's an oscillator which can be used as a tone generator, pulse generator, signal injector, and in other applications.

There's still another important variation of the flip-flop circuit, the *monostable multivibrator.* This circuit isn't free-running like the astable multivibrator, and as with the flip-flop, an input pulse is needed to trigger it. But instead of changing states each time an incoming signal is received, the monostable multivibrator issues a single pulse for each incoming pulse. At first that may not sound too useful, but since the pulse width from the monostable multivibrator is completely independent of the incoming pulse width, it's actually a very useful circuit. For example, the circuit can be used to stretch or narrow incoming pulses.

We'll see how to use the 914 as a monostable multivibrator in the next chapter, but first let's try it in an astable mode.

CIRCUIT ASSEMBLY

Figure 6-1 shows how the gates inside the 914 are connected to produce an astable or free-running state, and Figure 6-2 shows how to connect the 914 in a practical circuit. I assembled the prototype oscillator on a perfboard, as shown in Figure 6-3, but since only a few external parts are required you can assemble the entire circuit by merely soldering the components to the IC mounting board.

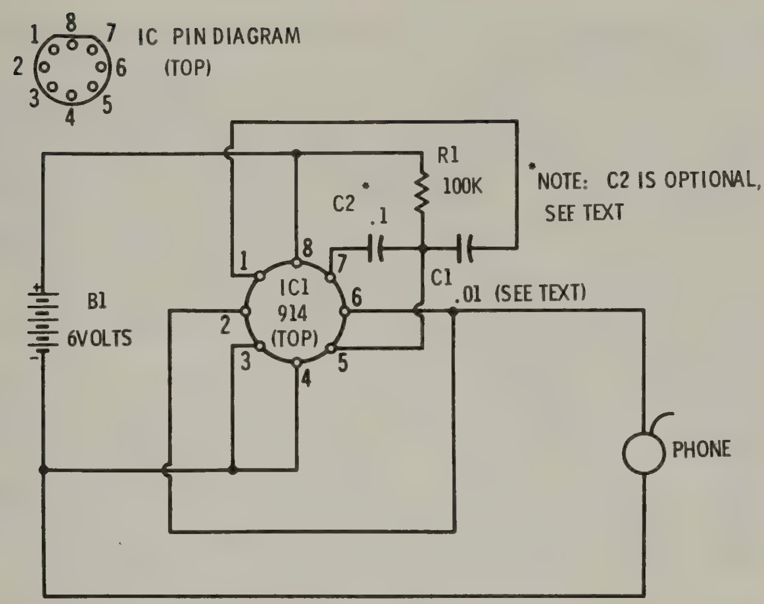


Figure 6-2. Digital IC oscillator circuit diagram.

Begin construction by soldering the 914 IC to a socket adaptor board. Spread the leads slightly and insert them into the board from its top (bare) side. Leave two holes between pins 1 and 8. When the leads are in place, invert the board and solder

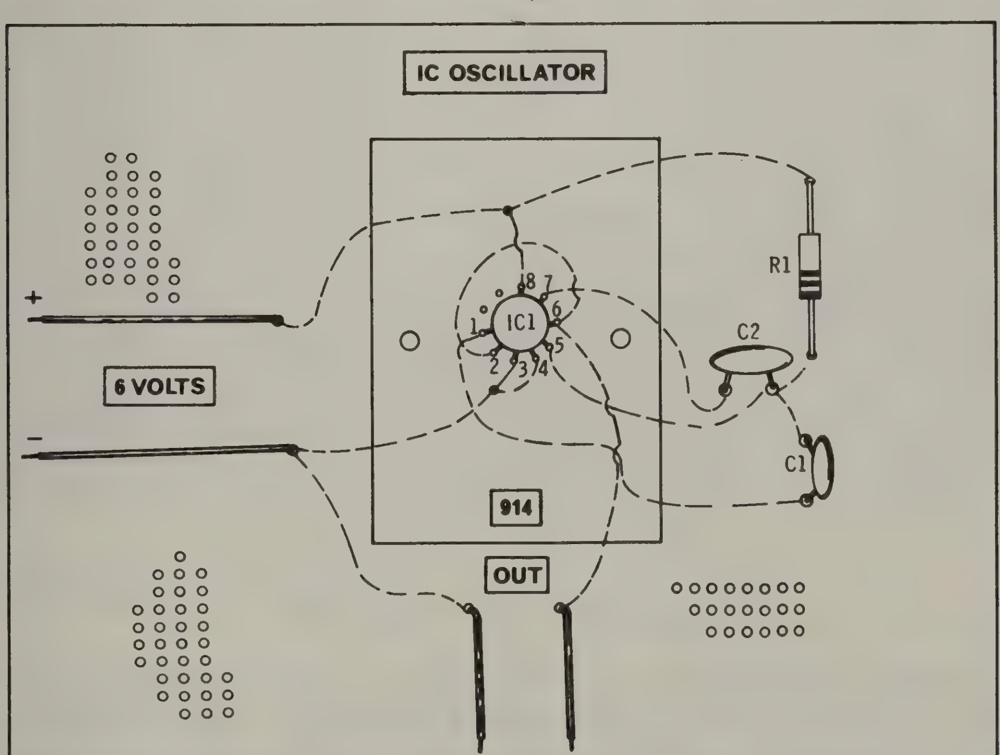


Figure 6-3. Digital IC oscillator pictorial.

them to the copper foil. Use two clothespins to hold the board in place during soldering.

Be sure to check the IC's pin diagram before soldering the IC to the board. The pin diagram, which is included in Figure 6-2, is viewed from the *top*. I generally mark each pin number next to the respective solder pad on the back of the adaptor board to save time and prevent confusion. Double check the pin diagram in Figure 6-2, and remember it shows the IC from the top, or you will reverse the pin markings.

When the IC is installed on the socket adaptor board, solder 4-inch lengths of insulated hookup wire to each of the solder pads. Even though several of the pins will be connected together later, it's more convenient to connect them with the connection leads instead of soldering bridge wires between pads. In this way, you can use the same 914 in several projects (including the one described in the next chapter) without having to disconnect soldered bridge wires.

When the leads are in place, insert them through holes in the perfboard and allow the adaptor board to stand about half an inch from the main board. Bend all the leads outward to keep the board in place, and install C1, C2, and R1. C2 isn't necessary for the circuit to oscillate, so you can eliminate it if you prefer. Or, you can include it in your circuit and experiment with bridging a wire across its terminals as I did with the prototype circuit.

Secure C1, C2, and R1 in place by bending their leads outward, and then solder one lead from C1 to one from C2. Solder the nearest lead from R1 to the junction formed by C1 and C2. Next, solder the remaining lead of R1 to the connection lead from the IC's pin 8. The remaining lead of C1 is soldered to the IC's pin 1. C2's free lead is soldered to pin 7's connection lead. If you omit C2, just solder pin 7's connection lead directly to the junction of R1 and C1.

Continue assembly of the oscillator by soldering the IC pin connection leads to one another as shown in Figure 6-3. Pin 3 goes to pin 4, and pin 2 goes to pin 6. Finally, pin 5 goes to the junction of C1, C2, and R1.

Complete assembly of the oscillator by connecting power supply and output leads. An insulated connection wire soldered to pin 8's connection lead becomes the positive (+) connection, and a second lead soldered to the junction of pins 3 and 4 be-

comes the minus (−) connection. Output leads are soldered to pins 3 and 4 and pin 6.

The completed circuit should resemble the prototype shown in Figure 6-4, if you used a perfboard. The circuit will be considerably more compact if you soldered all the parts directly to the IC's socket adaptor board.

If you didn't trim the connection leads from the IC mounting board before soldering them together, the wiring behind the perfboard will resemble a rat's nest. This will not affect operation of the circuit, and the extra lead lengths will permit you to modify the circuit for the next project. Just be sure to wrap some short lengths of electrical or masking tape around each exposed solder connection to prevent possible electrical shorts. A short can quickly ruin the 914 IC.

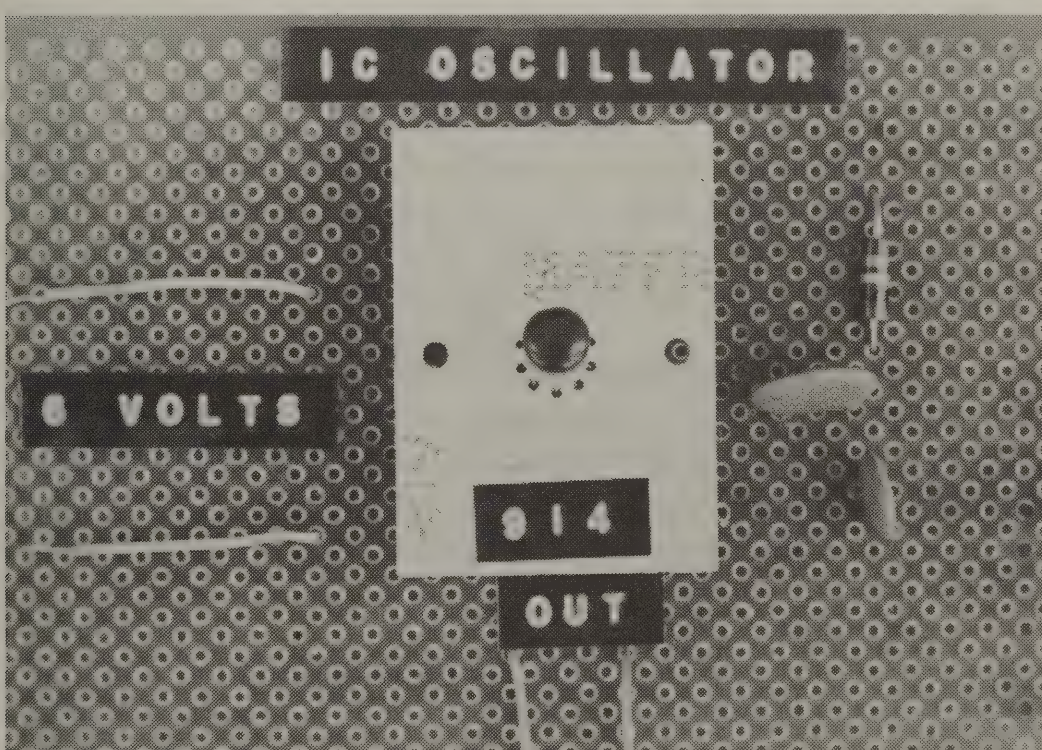


Figure 6-4. Assembled oscillator.

TESTING AND OPERATION

Carefully check all the circuit connections and recheck the pin connections to the 914 IC before connecting the complicated oscillator to a source of power. Make sure there are no shorts and remove any wire clippings or solder fragments.

When you are confident the circuit has been wired correctly, connect a crystal earphone to the output leads and a line-operated power supply or a 6-volt lantern battery to the plus and minus terminals. Don't use a higher voltage battery or the IC may be permanently damaged or destroyed.

When the power is connected, you should immediately hear a tone from the earphone. The tone will be very pure in quality and should have plenty of volume. If you don't hear a tone, disconnect the power supply or battery and recheck the wiring. Check for possible disconnected leads on the IC socket adaptor. If you're using a battery, make sure it's good by having a technician test it. Also, check the earphone to make sure it operates properly.

When the circuit is operating properly, you can try it as a tone generator, signal injector, code practice oscillator, or even a voltage controlled oscillator (VCO). No modifications are necessary to use the unit as a basic tone generator, but you can change C1 to get a variety of different frequencies. As a sample of what you can get, using a 0.01-μF capacitor for C1 as specified in the Parts List and a power-supply voltage of 4 volts will give a tone frequency of about 1.2 kHz (1200 cycles per second). Increasing the voltage will increase this frequency.

You can slow the tone down considerably by increasing C1. For example, with a 4-volt power source, I measured a frequency of only about 1200 Hz with a 0.1-μF capacitor. More spectacular results occur when you decrease C1. At 0.0022 μF and a 4-volt power supply, I measured an output tone of 5 kHz. With a 0.0001-μF capacitor, the tone increased to 90 kHz.

You obviously cannot hear a tone with a frequency of 90 kHz, but you can use an oscilloscope to see the signal. Just connect the scope across the output leads. If you don't have a scope, you can use an ordinary transistor radio to convert the high-frequency output of the oscillator into an audible frequency. Just place the radio near the oscillator and rotate the tuning dial until the tone (there may be several) is heard. Make sure the tone is coming from your oscillator by disconnecting the power momentarily.

It's interesting to note that when you change the value of C1, the width of the output pulses changes also. For example, with the 0.1-μF capacitor, the pulse width will be about 7.5

milliseconds (thousandths of a second). But with the 0.0001-μF capacitor, the pulse decreases to a width of only 10 microseconds (millionths of a second). This demonstrates the *time-constant* of a capacitor. As you can see, the smaller the capacitor, the faster it charges and discharges. This causes both a faster frequency and pulse width when the capacitor is used as a timing device in an oscillator.

GOING FURTHER

As I noted a few paragraphs ago, you can use the 914 IC oscillator as a voltage controlled oscillator (VCO). VCOs are frequently used in telemetry systems, since they can encode a variable voltage signal from a sensor or transducer into a variable tone. The tone is transmitted to a receiver some distance away and decoded by converting the tone into the voltage from the remote sensor. Temperature, rocket roll rate, pressure, and many other kinds of information can be telemetered with the help of a VCO.

To use your 914 oscillator as a VCO, simply connect a variable power supply to the plus and minus terminals and adjust the voltage back and forth between 0 and 6 volts. Don't exceed 6 volts or the IC will be damaged.

Using the prototype oscillator as a VCO, I found that oscillation would begin with a power-supply voltage of only 0.625 volts. At 1 volt and with a 0.0022-μF capacitor for C1, the output tone had a frequency of 2.8 kHz. At 3 volts, the frequency was 4.5 kHz; at 6 volts, it was 5.0 kHz.

Table 6-1. IC Oscillator Parts List

Item	Description
B1	Battery, 6 volt
C1	Capacitor, 0.01 μF (272-1065)
C2	Capacitor, 0.1 μF (272-1069)
IC1	RTL 914 dual 2-input gate (276-015)
R1	Resistor, 100,000 ohm
Misc	Crystal earphone (or use a crystal microphone), perforated board (276-1392), IC socket adaptor (276-028), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

Try some of these different applications of the basic 914 IC oscillator yourself. You might even want to install a rotary switch connected to several capacitors in order to rapidly change C1's value. Then try the same 914 IC in the next project, a monostable multivibrator.

CHAPTER 7

IC TONE STEPPER AND SQUARE-WAVE GENERATOR

In the last chapter we saw how to use the RTL 914, a low-cost digital IC, as an oscillator. In this chapter we're going to use this same IC as a monostable multivibrator.

As you will recall from our discussion of multivibrators several pages ago, the monostable multivibrator simply issues an output pulse each time a trigger pulse is received at its input. Since the height and width of the output pulse is completely independent of the input pulse, the monostable multivibrator can be used in several unusual and very useful applications.

Before describing how the circuit operates, let's settle on a more convenient name for the monostable multivibrator. Engineers call bistable multivibrators "flip-flops," so we're going to call the monstable a "one-shot." One-shot is easier to remember and tells you exactly what a monostable circuit does: it "shoots" out one pulse in response to an incoming trigger pulse.

HOW IT WORKS

In the previous circuit we used the 914 IC as an oscillator by connecting the output of each of the 914's to their respective inputs. By leaving one of the remaining gate inputs discon-

nected, the circuit will not oscillate but will issue an output pulse each time a trigger pulse is sent to the unconnected gate input.

To see how this works in a practical circuit, see the logic diagram in Figure 7-1. Note that the connections to the two gates are identical to those in the previous project (see Figure 6-1). However, the input to the gate formerly connected to a capacitor is now disconnected and used as the input terminal to receive incoming trigger pulses.

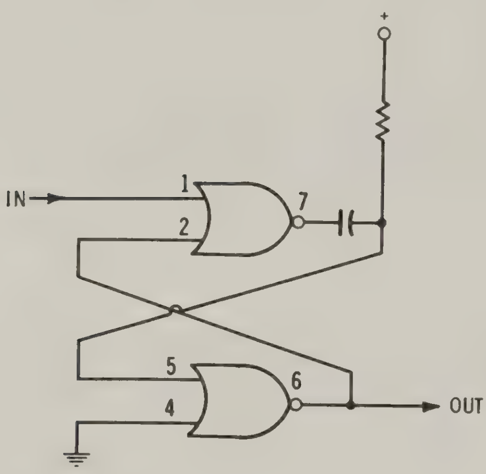


Figure 7-1. Monostable multivibrator logic diagram.

You can build and operate the circuit shown in Figure 7-1 by supplying your own trigger pulses, but the circuit in Figure 7-2 is far more convenient, since it incorporates a self-contained pulse generator. The pulse circuit is a unijunction transistor (UJT) oscillator, similar to the one used in the decade counter project in Chapter 5.

Operation of the UJT pulse generator is straightforward. Capacitor C1 charges through potentiometer R1 until the UJT conduction voltage is reached. When this occurs, C1 discharges through the UJT and R3 in a very quick pulse. The pulse is then sent to the input of the 914 one-shot circuit, where it triggers an output pulse.

In the last chapter you saw how the value of a capacitor can control both the frequency and width of pulses from an oscillator. Small-value capacitors give narrow pulse widths and large values wide pulse widths. In this circuit, a capacitor is used in this same role. The trigger pulse from the UJT oscillator is very fast, but by using a suitable capacitor for C2, we

can significantly increase the width of the output pulse from the one-shot. In the last circuit we altered the pulse width (and oscillation frequency) by changing the value of the capacitor, but it's possible to do the same thing by placing a resistor in series with the capacitor. By increasing the value of this resistor, the capacitor cannot charge or discharge as fast. In Figure 7-2, R4 and R5 are the series resistors which perform this function. R5 is a potentiometer, and R4 is a fixed resistor in series with R4. R4 is designed to keep some resistance in the circuit, in case R5 is rotated to the point where its resistance is almost zero.

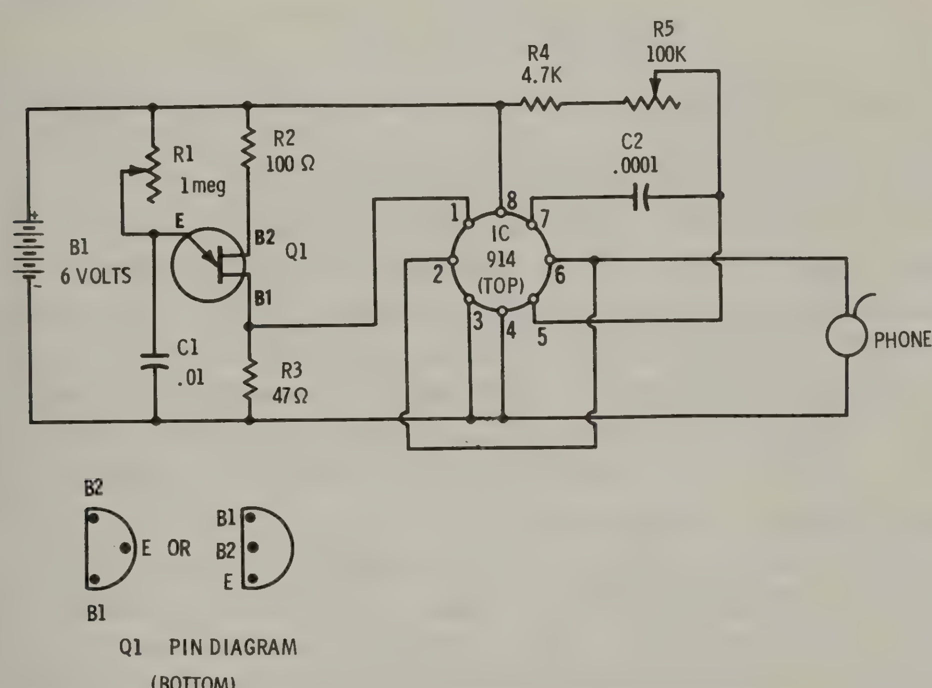


Figure 7-2. Digital IC tone stepper circuit diagram.

The output of the one-shot circuit is a series of pulses at the same frequency as the UJT trigger pulses but with more uniform characteristics and adjustable width. While the UJT pulse has a very fast rise and relatively slow fall time, the one-shot pulse is a perfect square wave. Figure 7-3 shows the relationship between the input and output pulses.

The completed circuit in Figure 7-2 is very useful as a compact square-wave generator, and we'll discuss this application in the section on "Testing and Operation." But the circuit can also be used as a tone stepper. By appropriate adjustments of R1, R5, and possibly C2, you can cause the output pulse from

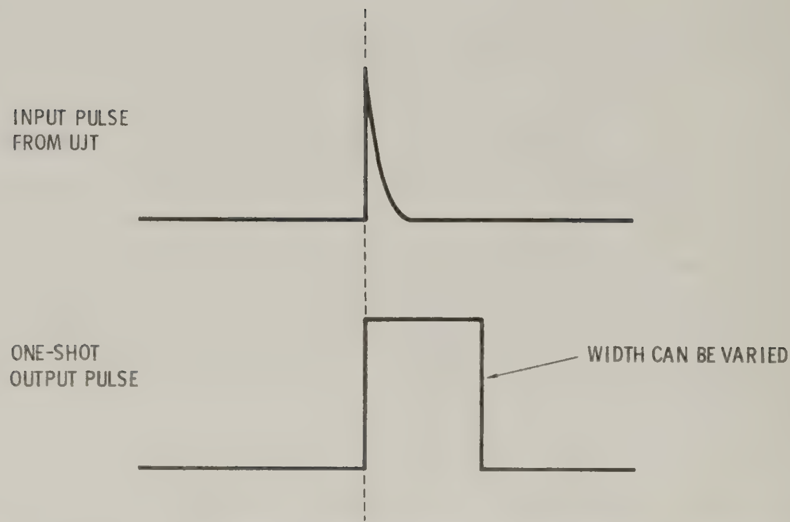


Figure 7-3. Input pulse from UJT and output pulse from one-shot.

the one-shot to be wider than the space between incoming trigger pulses from the UJT oscillator. For example, if a second trigger pulse from the UJT oscillator occurs before the end of the one-shot's output from a preceding trigger pulse, then the one-shot will issue only one output pulse for every two trigger pulses. If the trigger pulses are speeded up by reducing R1's value, or if the one-shot pulses are increased in width by increasing R5's value, the one-shot will issue even fewer output pulses for each trigger pulse.

In this role, the one-shot is actually acting as a *frequency divider,* an important digital logic device. The result is a very unusual tone sequence, when both R1 and R5 are adjusted. The tone steps through a range of separate frequencies without going through intermediate frequencies. Suitable manipulation of the shafts on R1 and R5 will produce a sound which closely resembles the music produced by bagpipes.

Figure 7-4 is a diagram showing how the one-shot divides an incoming pulse train by 2 or more, depending on the width of its output pulse. We'll discuss how you can display this on an oscilloscope in the section on "Testing and Operation," but first let's assemble the circuit.

CIRCUIT ASSEMBLY

You'll need a perfboard to asemble the one-shot and pulse generator circuits, since there are too many components to

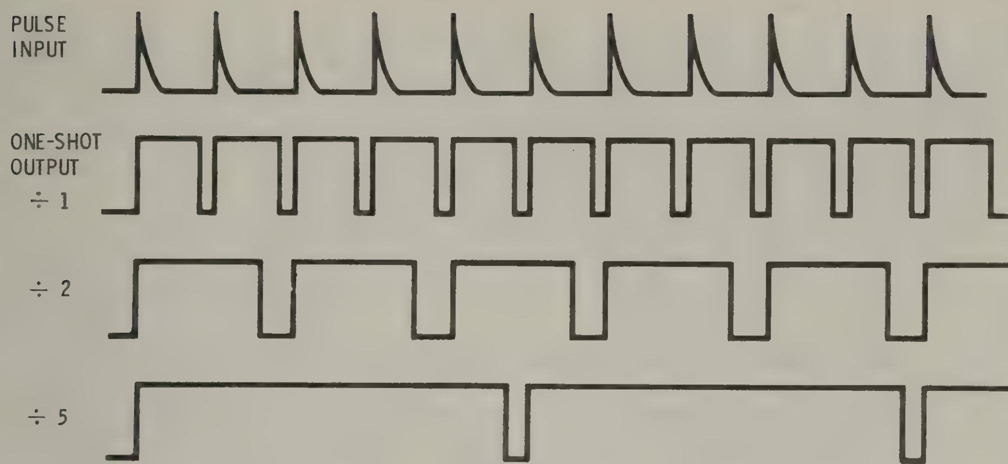


Figure 7-4. Frequency division with a one-shot.

mount on a socket adaptor board alone. You can use the 914 from the previous projects if you like. In fact, you can assemble this circuit directly on the 914 oscillator project perfboard.

For details on mounting the 914 to a socket adaptor board, see the "Circuit Assembly" section of Chapter 6. When the IC is soldered to the board, and lengths of hookup wire have been soldered to the solder pads, install the IC into the perfboard by threading the connection leads on the adaptor board through holes in the perfboard. Bend the leads outward to hold the assembly in place.

Next, install the remainder of the one-shot components: C2, R4, and R5. I secured R5 in place with connection leads soldered to its central terminal and one outer terminal. For a more permanent assembly, however, you can mount R5 in a 3/8-inch hole bored in the perfboard. Solder one lead of R4 to the IC's pin 8 connection lead and the remaining lead to one of R5's outer terminals. Then solder one of C2's leads to the IC's pin 7 connection lead and the remaining lead to R5's center terminal.

Complete assembly of the one-shot by soldering the IC connection leads for pins 3 and 4 together. Do the same with the leads for pins 2 and 6. Then solder a length of hookup wire to the IC's pin 6 connection lead and another to the negative power-supply connection point, and thread both wires through adjacent holes in the perfboard. These provide the output connections for the one-shot.

Begin assembly of the UJT pulse generator by inspecting UJT Q1 to determine the identification of the 3 leads. See Figure 7-2 for Q1's base diagram. Insert Q1 in the board, as shown

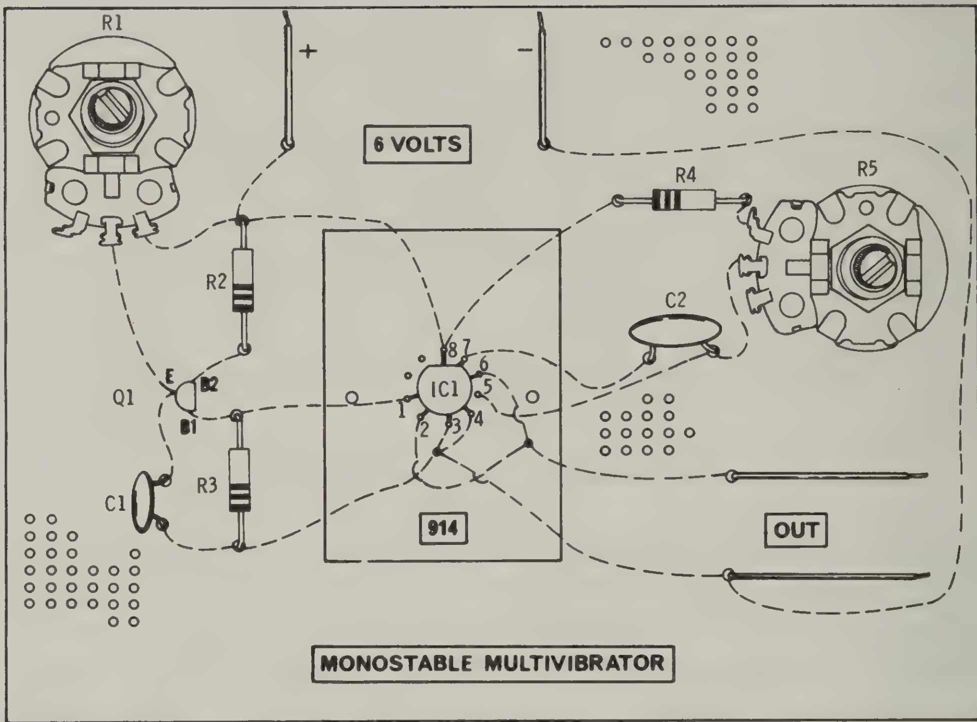


Figure 7-5. IC tone stepper pictorial.

in Figure 7-5, and bend its leads outward slightly to temporarily hold it in place. Then install C1, R2, and R3 and bend their leads outward also. Solder C1, R2, and R3 to the UJT as shown in the pictorial in Figure 7-5.

Next, solder a length of insulated hookup wire from the junction of C1 and R3 to the junction of the IC's pins 3 and 4. This becomes the negative power-supply connection. Solder a second hookup wire to this connection and thread it through a hole in the perfboard.

Complete assembly of the pulse generator by installing potentiometer R1. As with R5, you can mount R1 in a 3/8-inch hole bored in the perfboard or secure it in place with connection leads soldered to its center and one outer terminal. When R1 is mounted in place, solder the center terminal's connection lead to Q1's emitter and the remaining lead to R2's free lead. Then solder a length of insulated connection wire from the junction of R1 and R2 to the IC's pin 8 connection lead. This connection will become the positive power-supply input point. Solder a second hookup wire to this connection and thread it through a hole in the perfboard adjacent to the negative connection hookup wire.

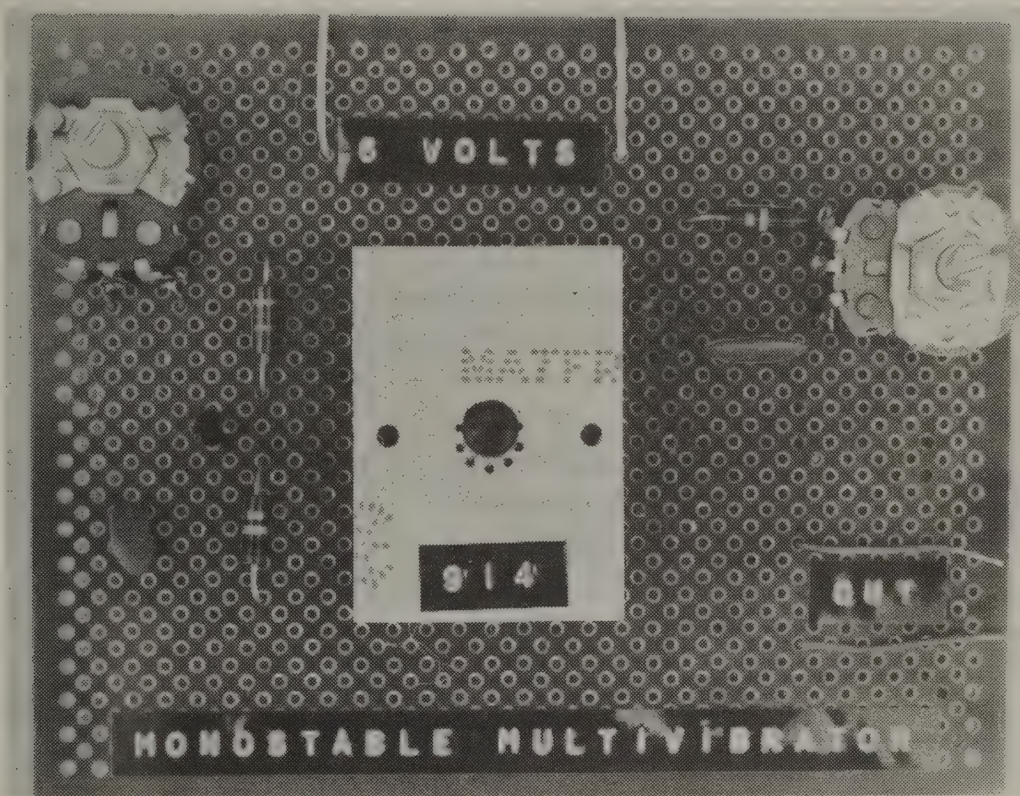


Figure 7-6. Assembled monostable.

All that remains to complete the project is a connection wire from Q1's B1 to the IC's pin 1 connection lead. The completed circuit should resemble the prototype shown in Figure 7-6.

TESTING AND OPERATION

This project has more wiring than the basic 914 IC oscillator; so be sure to check all the connections for possible wiring errors. Make sure the UJT is installed properly, and use electrical tape to insulate all exposed solder connections which might cause a short.

When you are confident the circuit is properly assembled, connect 6 volts from a line-operated power supply or lantern battery to the positive and negative connection points. With a crystal earphone connected to the output, you will immediately hear a musical tone if the circuit is operating. If not, try rotating R1's shaft. If no tone is heard, disconnect the power source and recheck all the wiring and both IC and UJT pin connections.

When the circuit is operating, you will hear the stepped tones (the unique electronic bagpipes I described earlier) by adjusting R1 and R5. Try laving R5 set at one point while rotating R1 for best results. To change the frequencies of the stepped tones, readjust R5 slightly and continue rotating R1's shaft.

Changing the value of C2 will also alter the tone stepping (frequency division) characteristics of the circuit. Larger values will cause a longer output pulse from the one-shot; hence, you will get increased division. You should easily get 5 to 6 discrete tone steps and as many as 10 with careful adjustment of R1 and R5.

If you are interested in learning more about the operation of the tone stepper, take the completed circuit to a school electronics lab or TV repair shop equipped with a dual-trace oscilloscope. A courteous request should earn you permission to connect the circuit to the scope. Don't be afraid to ask for help in setting up the scope controls for the experiment.

Connect one scope probe to the output of the UJT oscillator (B1 of the UJT) and ground. After adjusting the scope controls, you'll see a regularly spaced series of spikes across the screen.

Connect the second probe to the output of the one-shot (pin 6) and ground. Adjust the scope so the second trace is below the first, and you should see a series of square waves below each pulse from the UJT, as shown in Figure 7-4. Rotate R1 and R5 as before, and you will see a fascinating sequence of events on the scope as frequency division takes place. Try to divide as many UJT pulses into a single one-shot pulse as possible. Also, try connecting additional capacitors (e.g., 0.1- and 0.01-μF units) directly across C2's leads. For best results, listen to the tone with the earphone while watching the patterns on the scope.

The square-wave output from the one-shot can be put to practical use in analyzing the performance of an amplifier. By using a 0.0001-μF capacitor for C2 and with suitable adjustment of R5, the circuit will generate pulses less than 0.2 microseconds wide. The pulses will have very fast rise and fall times; in other words, they are square in appearance. They are, therefore, useful for checking the frequency response of high-frequency amplifiers. Use a larger capacitor to check audio amplifiers.

GOING FURTHER

In this project, we made up our own one-shot by wiring up two gates in a 914 IC, but you can duplicate the same experiments described above by using a true IC one-shot, the 74121 monostable multivibrator (Radio Shack 276-1814). This IC is more flexible, and suitable adjustment of the timing circuit (C1 and R1 in Figure 7-1) permits output pulses ranging from 40 nanoseconds to 40 seconds.

Table 7-1. IC Tone Stepper Parts List

Item	Description
B1	Battery, 6 volt
C1	Capacitor, 0.01 μF (272-1065)
C2	Capacitor, 0.0001 μF (272-123; see text)
IC1	RTL 914 dual 2-input gate (276-015)
Q1	Transistor, unijunction (276-111)
R1	Potentiometer, 1,000,000 ohm (271-211)
R2	Resistor, 100 ohm
R3	Resistor, 47 ohm
R4	Resistor, 4700 ohm
R5	Potentiometer, 100,000 ohm (271-092)
Misc	Earphone, crystal (33-175) (or use crystal microphone); perforated board (276-1392); socket adaptor (276-028); hookup wire; solder

Radio Shack catalog numbers shown in parentheses.

CHAPTER 8

HIGH-GAIN AUDIO AMPLIFIER

If you've ever wondered what a softly ticking watch *really* sounds like, this amplifier project is for you. In fact, with this high-gain amplifier, you will be able to easily hear such "silent" sounds as an ant walking across a microphone.

The secret to the unusually high gain of this project is a 741 operational amplifier IC. The 741 is an advanced version of the popular 709 "op amp," one of the most widely used non-digital integrated circuits. Both of these very useful ICs are available for less than a dollar each from Radio Shack, and we'll be working with both of them in these last chapters.

HOW IT WORKS

If you've read Radio Shack's *Introduction to Transistors and Transistor Projects,* you already have an idea of how a transistor amplifies. In simplest terms, amplification occurs when a small current flow at the transistor's base alters a much larger current flow from the emitter to the collector (or collector to emitter). The transistor simply permits an incoming signal to modulate and control a much larger current from a battery or other source of current.

As you probably know, connecting two or more transistors in series permits very high amplification to be obtained. For example, a single transistor may have a gain of 100, but two

transistors with this gain connected in series will give a gain of 10,000. Integrated circuitry permits multiple transistor amplifiers to be assembled on tiny silicon chips, and the 709 and 741 are excellent examples of such IC amplifiers.

Both the 709 and 741 are op amps. The operation of the op amp is a complicated subject, but a few basics will get you through most op amp projects with no problems. First, the op amp consists of a *differential amplifier,* followed by several stages of additional amplification. A differential amplifier is distinguished from other amplifiers in that it has two input terminals. One terminal is called the inverting input (−) and the other the non-inverting input (+). As you can see in Figure 8-1, a signal applied to the inverting input is inverted by the op amp, while the polarity of a signal applied to the non-inverting input is unaffected. For more on inversion, see Chapter 3.

The two inputs of the op amp make for several very interesting characteristics. For example, the op-amp's output is zero when the same signal is applied to both inputs. This is because the inverting input gives an output exactly out of phase with the non-inverting input, and the two cancel one another. This feature is convenient for eliminating undesirable hum or other stray signals.

The 709 op amp has some 15 transistors and 14 resistors. Because of its very high gain, a few small capacitors must be

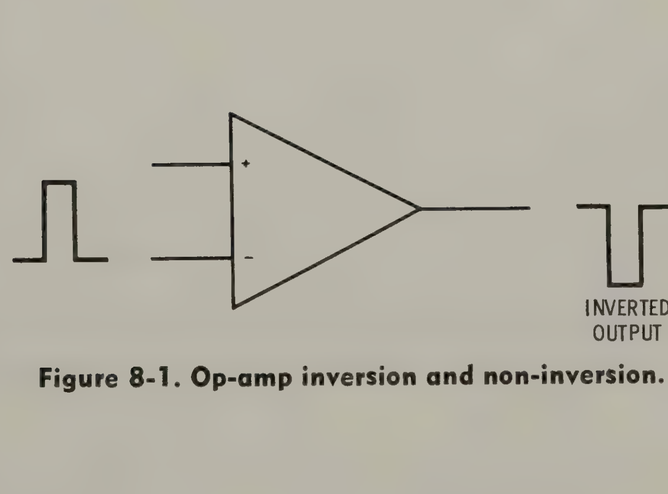


Figure 8-1. Op-amp inversion and non-inversion.

connected to the device to prevent oscillation from occurring. The 741 is a more sophisticated version of the 709 and incorporates internal compensation circuitry to prevent oscillation. In the next chapter, I'll show you how to make an op amp oscillate under controlled conditions. Now, however, we're going to assemble a high-gain audio amplifier using an op amp, and oscillation is the last thing we want to occur.

Operation of the circuit can be seen by referring to the diagram in Figure 8-2. The high input impedance of the 741 permits any general-purpose crystal microphone (or earphone) to be fed into the op amp. Potentiometer R2 serves as a volume control. R3 is a feedback resistor which stabilizes the amplifier and controls its gain and frequency response. The output of the 741 is low impedance; so an inexpensive magnetic earphone can be used to hear the amplified signal.

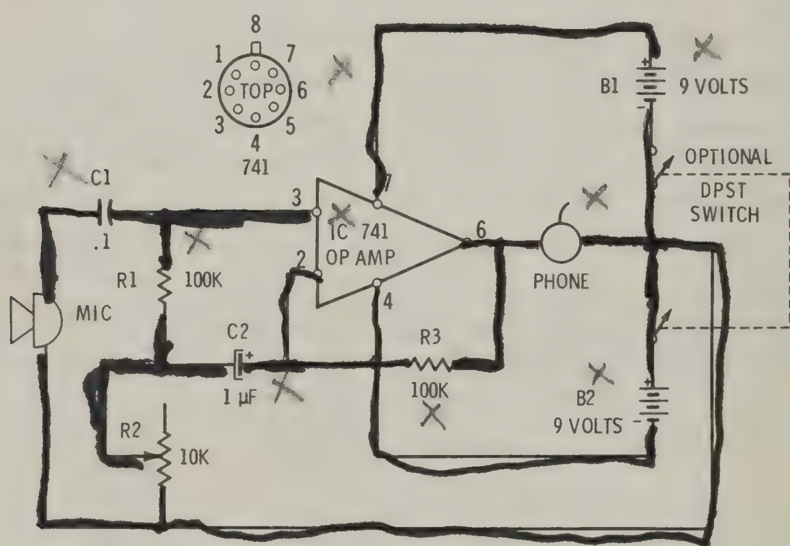


Figure 8-2. High-gain op-amp audio amplifier circuit.

CIRCUIT ASSEMBLY

Begin assembly of the amplifier by soldering a 741 IC to a socket adaptor board and soldering connection leads to each solder pad; use the procedures outlined in previous chapters. Use 4-inch lengths of connection wire. When the IC board is completed, thread the connection leads through the perfboard and allow the assembly to stand about half an inch above from the perfboard. During assembly, try to keep the IC connection leads fairly short by trimming excess lengths. If the

wires are left fairly long, their proximity to other leads may cause undesirable oscillation to occur.

Next, install C1, R1, and C2 in the approximate positions shown in the pictorial in Figure 8-3. Solder R1 from one terminal of C1 to the negative terminal of C2. C1's remaining lead will become one of the input leads. Solder the connection lead from the IC's pin 3 to the junction of C1 and R1.

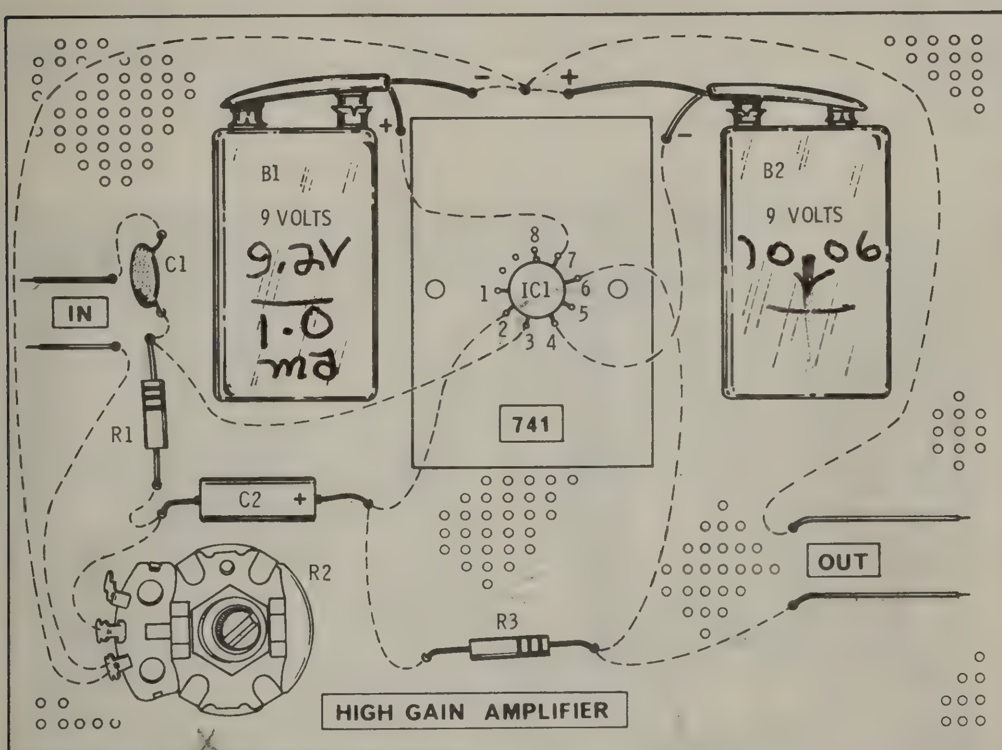


Figure 8-3. Op-amp high-gain amplifier pictorial.

Continue assembly of the circuit by inserting R3 into the perfboard, as shown in Figure 8-3, and soldering one of its leads to the connection lead for the IC's pin 6. This connection will become the amplifier's output; so solder a length of insulated hookup wire to it and thread it through the perfboard. R3's remaining lead goes to C2's remaining lead, and the resulting junction is soldered to the IC's pin 2 connection lead.

Complete the component installation by mounting the volume control, R2, to the perfboard by its connection leads. For a sturdier assembly, mount R2 in a ⅜-inch hole bored in the board. R2's center terminal should be connected to the junction of R1 and C2 with a short length of hookup wire. A length of hookup wire soldered to one of R2's outer terminals serves as

the second input connection. Thread the wire out through a hole in the perfboard near the first input lead.

Complete assembly of the amplifier by installing two 9-volt battery clips. Thread the leads from each clip through the perfboard, as shown in Figure 8-3, and solder the black lead from one clip to the second clip's red lead. Then solder two lengths of insulated hookup wire to the resulting junction. One wire becomes the second output terminal and should be threaded through a hole in the perfboard adjacent to the first output terminal. The second wire goes to the terminal of R2, which serves as an input connection.

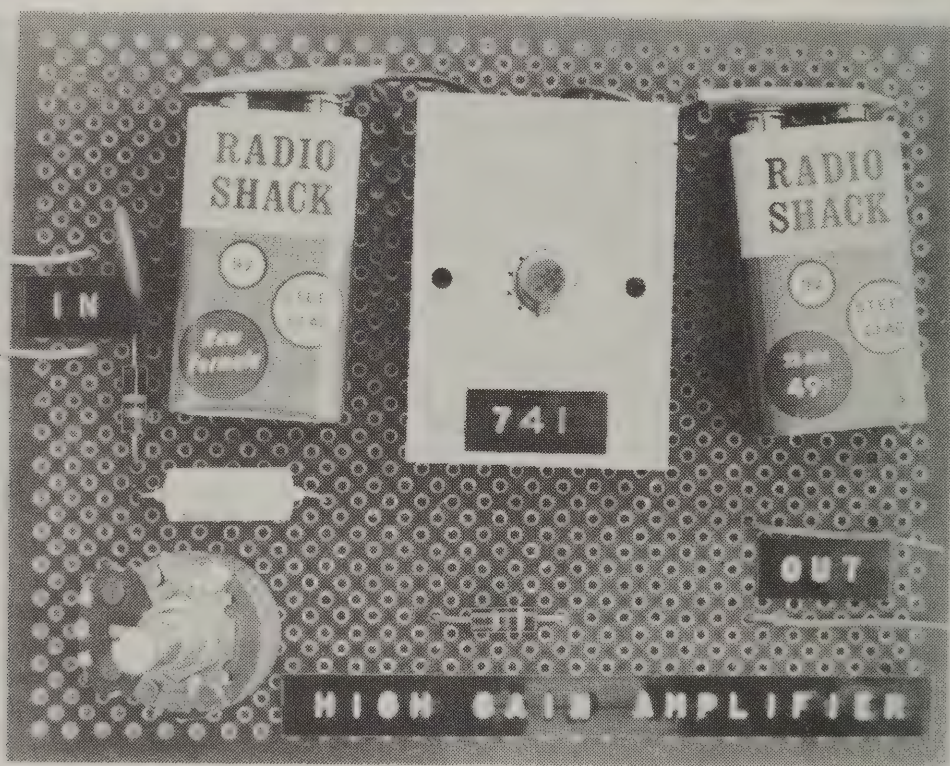


Figure 8-4. Assembled amplifier.

The connections you have just made are all called ground connections. The op amp requires a bipolar power supply for proper operation, and we're going to achieve this requirement by using two series-connected 9-volt batteries. The positive supply is obtained by soldering the unused red battery clip lead to the connection lead for the IC's pin 7. The negative supply is obtained by soldering the unused black lead to the connection lead for the IC's pin 4.

Assembly of the amplifier is now complete, and the finished circuit should resemble the prototype shown in Figure 8-4. Carefully inspect the circuit for possible wiring errors and shorts before installing the batteries.

TESTING AND OPERATION

When you have inspected the wiring for possible errors, connect a 9-volt battery to each battery clip. The circuit is turned off by disconnecting the batteries. With a crystal microphone connected to the input and a magnetic earphone at the ouput, you should be able to hear a shrill oscillation by placing the earphone near the microphone. The oscillation occurs when noise from the amplifier is picked up by the microphone and reamplified. This process is called *positive feedback,* and the result is a high-pitched tone.

If the tone isn't present, try adjusting R2's shaft. If this doesn't help, disconnect the batteries and make sure both are good by having a technician check them. Then, reinspect the wiring for possible errors.

When your amplifier is working properly, place the microphone near a spring-driven clock or watch. The amplifier will increase the sounds from the mechanism greatly, and you'll be able to hear sounds you never knew a clock made. Another interesting experiment is to place a small square of paper over the microphone and allow an ant to walk across the paper. If the paper has good mechanical contact with the microphone, you should be able to hear the walking sounds of the ant. Most crystal microphones incorporate a foil diaphragm connected to the piezoelectric crystal element. For even better results, remove the microphone's cover and carefully place the ant directly on the diaphragm. Use care to avoid damaging the fragile diaphragm.

If you don't have a crystal microphone, you can use a crystal earphone instead. But you will get better results with a microphone, since it will have a larger diaphragm sound receiving area. You can artificially increase the sound receiving area of the earphone or microphone by mounting it in the focal region of a dish-shaped parabolic reflector. This sound antenna will permit you to hear sounds originating from several hundred feet away.

The gain of this amplifier is so high that oscillation may occur even when the earphone and microphone are widely separated. This is caused by inductive feedback resulting from the proximity of some of the connection leads, and you should be able to eliminate it by rearranging the wiring on the back side of the circuit board. In some cases, it might even be necessary to move one or more of the components to another part of the perfboard to eliminate the unwanted oscillation. But before going this far, disconnect the earphone to make sure acoustical feedback from the earphone to the microphone isn't causing the problem.

GOING FURTHER

The high-gain amplifier can be used in a variety of practical applications; so you might want to build it into a permanent plastic or metal cabinet. Radio Shack markets several such cabinets, and the 270-627, a bakelite case with aluminum front panel, is ideal for this project. You should cut the amplifier's perfboard down to the appropriate size and mount R1 in a hole drilled in the front panel. Also, mount input and output jacks in the panel to permit the microphone and earphone to be conveniently connected and disconnected.

If you do install the circuit in a case, be sure to include an on-off switch so that the amplifier may be turned off without removing the batteries. Wire the switch into the circuit as shown in Figure 8-2.

Table 8-1. High-Gain Amplifier Parts List

Item	Description
B1, B2	Batteries, 9-volt transistor radio
C1	Capacitor, 0.1 μF (272-1053)
C2	Capacitor, 1 μF (272-1055)
IC1	741 op amp (276-010)
Microphone	Crystal, (33-100)
Earphone	Magnetic (33-175)
R1, R3	Resistors, 100,000 ohm
R2	Potentiometer, 10,000 ohm (271-1715)
Misc	Perforated board (276-1392), IC socket adaptor (276-028), battery clips (270-325), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

If the oscillation characteristics of the amplifier circuit fascinate you, try causing the unit to intentionally oscillate by inserting a small-value capacitor (e.g., 0.01 μF) between the IC's pins 3 and 6. Depending on the value of the capacitor, the circuit will either oscillate or "motorboat." You might also want to experiment with the value of R3 to alter the gain of the amplifier and change the oscillation characteristics.

If you prefer using an op-amp circuit to generate oscillating waveforms rather than as an amplifier, see the next chapter. You'll find all the details on how to assemble an op-amp waveform generator using the 709, the 741's predecessor.

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CHAPTER 9

OP-AMP FUNCTION GENERATOR

A function generator is an instrument which generates a variety of periodic waveforms. Sound complicated? Not really, particularly since you've already generated periodic waveforms using both digital and op-amp transistor and IC circuits in several of the preceding chapters.

The operational amplifier is well suited for generating a wide variety of both conventional and unusual waveforms, many of which are ideal for troubleshooting and evaluating the performance of amplifiers. In this role, the function generator is commonly known as a signal injector or generator. Sending various wave patterns through an amplifier permits several important characteristics of the circuit undergoing test to be evaluated. For example, distortions in the shape of the waveform indicate poor performance, and the amplifier can be adjusted or modified until the distortion is minimized. An incoming wave of known height is very valuable for measuring the gain of the amplifier undergoing evaluation. One simply measures the output signal amplitude with an oscilloscope and divides this voltage by the voltage of the incoming signal to determine the amplifier's gain.

HOW IT WORKS

As you saw in the previous project, an amplifier will oscillate when its output is coupled back to its input. We did this on purpose in Chapter 8 by placing the amplifier's earphone near its microphone. If you tried the suggestions in the "Going Further" section, you might have also obtained oscillation by connecting a single capacitor into the circuit.

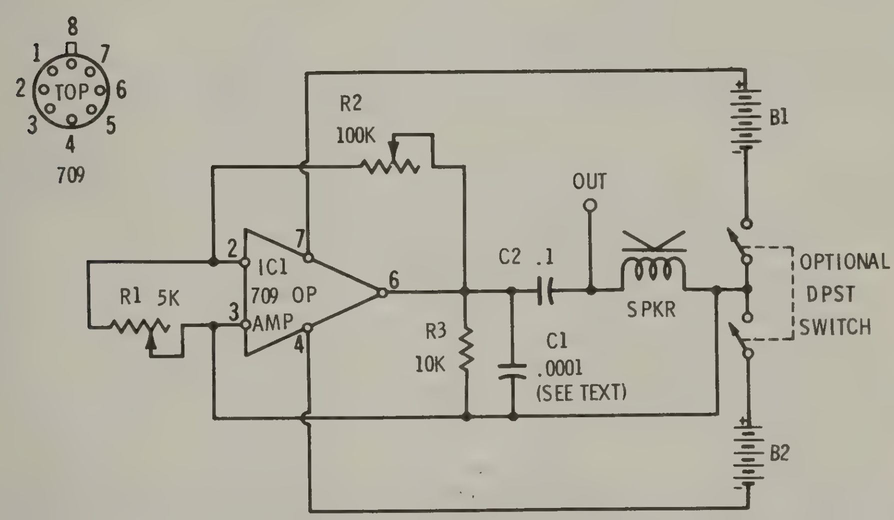


Figure 9-1. Op-amp function generator circuit.

Many op-amp function generators use two ICs to generate a family of waveforms, but we're going to use just a single 709, the non-frequency compensated version of the 741. Referring to the circuit diagram in Figure 9-1, note that feedback from the amplifier's output (pin 6) to its inverting input (pin 2) is provided by potentiometer R2. R2 and the network formed by R3 and C1 cause the 709 to oscillate at a frequency determined by the values of each of these three components. Depending on the adjustments of R1 and R2 and the value of C1, excellent quality sine- and triangle-wave patterns can be produced. Other adjustments will give other waveforms.

The circuit shown in Fig. 9-1 incorporates a speaker as an output device. In this mode, the circuit functions as a high-quality, adjustable tone generator. The speaker can be left in the circuit or removed when the function generator is used for signal injection.

CIRCUIT ASSEMBLY

Figure 9-2 is a pictorial view of the assembled function generator. Begin assembly of the project by mounting a 709 IC to a socket adaptor board, as described in previous chapters. Be sure to leave two spaces between pins 1 and 8. Also, mark the pin numbers adjacent to each solder pad to prevent possible confusion and wiring errors later.

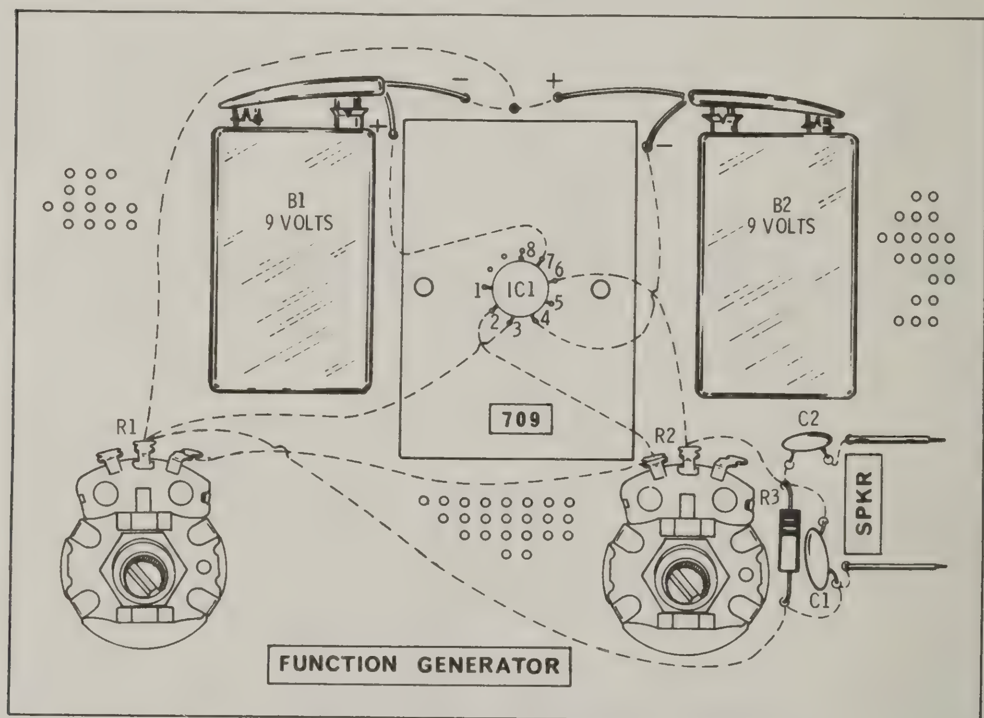


Figure 9-2. Function-generator pictorial.

When connection leads have been soldered to each of the adaptor board's solder pads, install the assembly into the perfboard. As with previous projects, leave the adaptor board about half an inch above the perfboard to facilitate resoldering of its connection leads if that should become necessary.

Next, install two 9-volt battery clips by threading their leads through holes in the perfboard. Solder the black lead from one clip to the red lead of the other to form the ground terminal. Later you will make additional connections to the ground terminal. The remaining black clip lead is soldered to the IC's pin 4 connection lead. The remaining red clip lead goes to the IC's pin 7 connection lead.

Continue assembly by installing potentiometers R1 and R2. As in the previous circuits using potentiometers, I mounted R1 and R2 to the perfboard with connection leads soldered to the central and one outer terminal. If you intend to experiment with the circuit for an extended period, install the pots in ⅜-inch holes drilled into the perfboard.

The center terminal of R1 is soldered to the IC's pin 3 connection lead, and then an insulated hookup wire is soldered from this connection to the ground terminal (the connection formed by the red and black battery clip leads). Avoid excess lead length by trimming the connection leads. This will preclude undesirable oscillation and give you total control over the completed circuit. Connect one outer terminal of R1 to the IC's pin 2 connection lead.

The center terminal of R2 is soldered to the IC's pin 6 connection lead, and one outer terminal is connected to the junction of R1 and pin 2. Again, avoid excessive lead lengths.

Next, insert C1, C2, and R3 into the perfboard as shown in Figure 9-3. Solder one lead from each of these components to one another, and then use a short length of insulated hookup

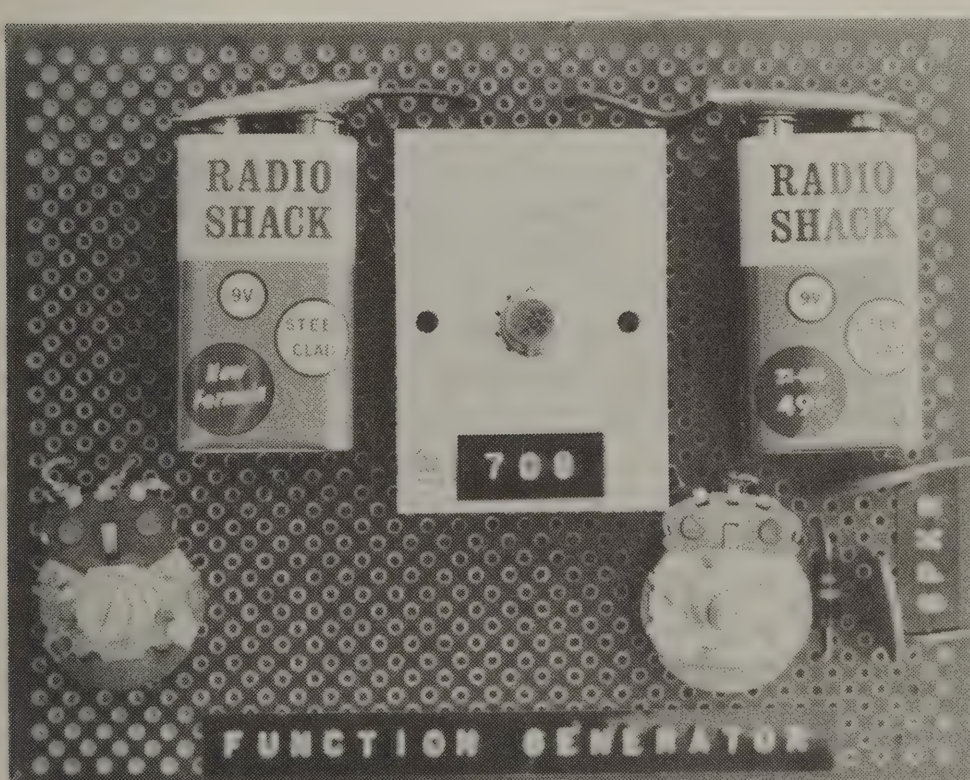


Figure 9-3. Assembled function generator.

wire to solder a "jumper" from this connection to the junction of R2 and the IC's pin 6. The remaining leads of C1 and R3 are soldered together, and a second "jumper" is soldered from this connection to the ground terminal.

Conclude assembly of the function generator by connecting a speaker to the remaining lead of C2 and the ground terminal. No output transformer is necessary, since the op amp has a low output impedance. The finished circuit should resemble the prototype unit shown in Figure 9-3.

TESTING AND OPERATION

When the circuit is complete, carefully inspect the connections for possible wiring errors before installing the batteries. Be sure the IC pins are correctly connected, since incorrect polarity might permanently damage the IC.

When you have inspected the wiring, temporarily install a 0.22-μF capacitor directly across C1's leads (you can use clip leads) and connect a 9-volt battery to each of the two battery clips. You should immediately hear a tone from the output speaker. If not, try rotating R1 and possibly R2. If a tone is still not heard, disconnect the batteries and recheck the wiring.

After the circuit is operating properly, you can experiment with its capabilities. For a very pure sounding note, set R1 at about its midpoint and use a 0.22-μF capacitor for C1. If you installed a 0.0001 μF for C1, just connect the leads of the 0.22-μF unit directly to the existing C1 to obtain the required value. Rotate R2's shaft to change the pitch of the tone.

If you have access to an oscilloscope, you can look at the output of the function generator directly. In the case of the settings just specified, you should see a triangle-wave pattern, as shown in Figure 9-4A, when the scope's probe is connected to the speaker terminals. As R2 is rotated in one direction, the waves become more closely spaced (their frequency increases) and their amplitude decreases.

The triangle wave is very useful in signal injector applications, though it is not often used in this role. The triangle wave is useful because any distortion of the wave is immediately obvious. For example, "clipping" will cause the waves to have flat instead of angular peaks. Frequency distortion will alter the nice, straight lines of each wave. Square- and sine-wave

generators are more commonly used for signal injection, but clipping is hard to detect with square waves, and frequency distortion isn't as obvious with sine waves.

After experimenting with the function generator's triangle-wave output, remove the 0.22-μF capacitor and set both R1 and R2 at their midpoints. You probably won't hear a tone from the speaker, but a transistor radio placed a few inches from the function generator should emit a high-pitched tone. It may be necessary to tune the radio over its reception band for best results. You should be able to pick up the signal several feet away from the circuit when the radio is properly tuned for best reception.

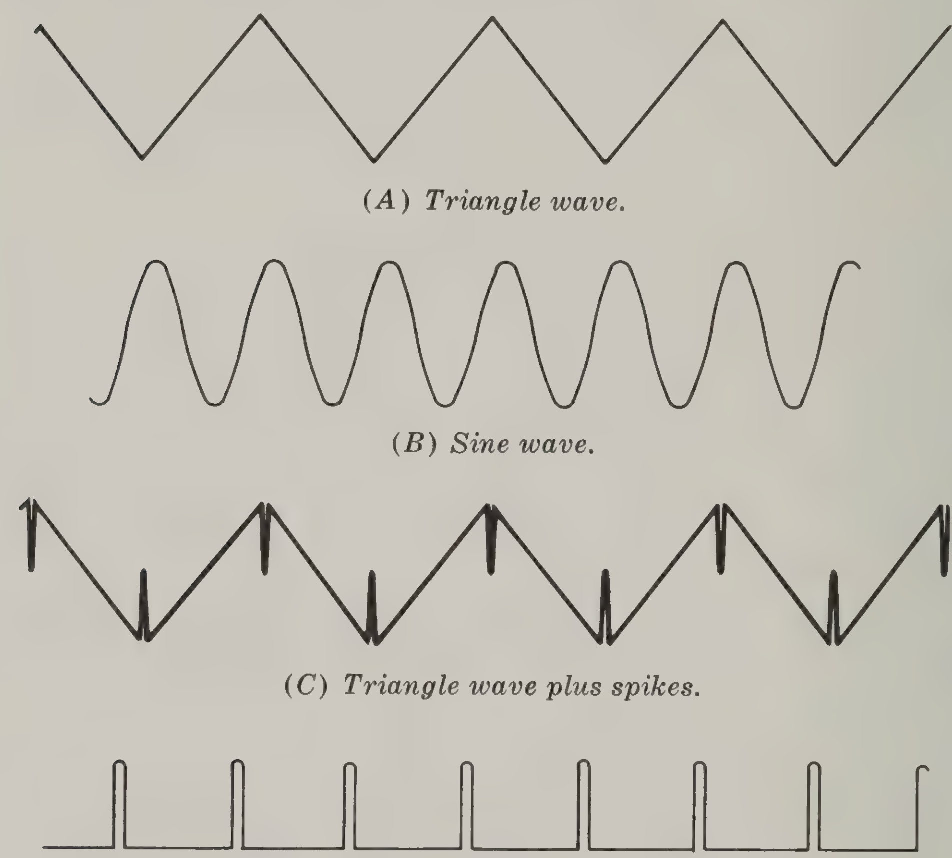
The output of the function generator without the 0.22-μF capacitor is a sine wave. With R1 set to 220 ohms and R2 at its midpoint, the wave has a frequency of 850 kHz (850,000 cycles per second), well beyond the range of human hearing. The radio detects this high-frequency wave and converts it to an audible tone. You can change the frequency of the wave by adjusting the value of C1. For example, try connecting a second 0.0001-μF capacitor across the first to slow down the frequency somewhat. A typical sine wave is shown in Figure 9-4B.

A third output of the function generator is the modified triangle wave shown in Figure 9-4C. The wave pattern consists of a triangle wave containing a spike from each positive and negative apex to ground.

To obtain this modified triangle wave, set R1 and R2 at their midpoints, and use the original 0.0001-μF capacitor for C1. The result can be viewed on an oscilloscope—a narrow spike at the apex of each triangle. The repetition rate (frequency) can be adjusted by rotating R2. For other effects, try changing the value of C1 by adding additional capacitance. All that's necessary is to connect extra capacitors in parallel to the original C1.

Finally, use the function generator to create a series of high-frequency pulses by disconnecting the speaker, setting R1 to about 15 ohms, R2 at about its midpoint, and using the original 0.0001-μF capacitor for C1. The result will be a series of spikes only about 2 microseconds wide, nearly 9 volts in amplitude, and occurring at a rate of 90 kHz (90 thousand per second). Rotate R1 and R2 slightly to change the repetition rate of the spikes. You may want to experiment with the circuit by increasing C1's value slightly.

As you can readily see, the function generator is a versatile device. You can perform all these tests with the speaker or radio as an output device, but try to obtain the use of an oscilloscope for best results. Since you can run through the tests fairly rapidly, a polite call to a school electronics lab or TV repair shop might result in some free scope time.



(A) Triangle wave.

(B) Sine wave.

(C) Triangle wave plus spikes.

(D) Spike.

Figure 9-4. Function-generator waveforms.

GOING FURTHER

Since the function generator has practical uses, you might want to install it in a permanent housing. You can use the perfboard construction technique, but be sure to trim the board so it will fit the housing. Radio Shack sells a variety of sturdy plastic and metal housings that are appropriate for enclosing a variety of different-sized circuits.

If you do install the circuit in a housing, be sure to use a DPST switch, connected as shown in Figure 9-1, to permit the

device to be turned on and off without having to remove the batteries. Wire the switch between the positive and battery connection leads and the circuit as suggested in the "Going Further" section of the preceding chapter.

The circuit will not necessarily oscillate without the speaker; therefore, mount a jack for the speaker on the front panel so that it can be connected when desired. Some hookup wire and a plug soldered to the speaker's terminals will let you connect the speaker to the circuit.

It's also a good idea to mount R1 and R2 directly to the housing to permit adjustment of the circuit. You can even use a rotary switch such as the Radio Shack 275-1385 to connect up to a dozen different capacitors in parallel with C1. This will result in some very unusual waveform possibilities.

When installing any of the simpler circuits described in this book in a housing, you can probably omit the perfboard completely and solder the components directly to the socket adaptor itself. This technique will result in a savings you can apply toward purchase of the case. For details on soldering parts to the socket adaptor board, see the flip-flop demonstrator project described in Chapter 2.

Finally, don't feel restricted by the values of R1, R2, and C1 provided in Figure 9-1 and the Parts List. With a little experimenting, you'll find that the function generator will produce a great variety of strange and unusual waveforms.

Table 9-1. Op-Amp Function Generator Parts List

Item	Description
B1, B2	Batteries, 9-volt transistor radio
C1	Capacitor, 0.0001 μF (272-123; see text)
C2	Capacitor, 0.1 μF (272-1069)
IC1	709 op amp (276-017)
R1	Potentiometer, 5000 ohm (271-1714)
R2	Potentiometer, 100,000 ohm (271-092)
R3	Resistor 10,000 ohm
Speaker	Speaker (40-245)
Misc	Perforated board (276-1392), battery clips, IC socket adaptor (276-028), hookup wire, solder

Radio Shack catalog numbers shown in parentheses.

INDEX

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An up-to-date DIRECT tube substitution guide. Includes more than 12,000 substitutions for all types of receiving tubes and picture tubes. Instructions accompanying each section guide the reader in making proper tube substitutions and explain how to cross-reference between sections for other substitutes.

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